PB80-181266

Field Tests of Industrial Stoker Coal-fired Boilers for Emissions Control and Efficiency Improvement - Site E

KVB, Inc.
Minneapolis, MN

Prepared for

Industrial Environmental Research Lab.
Research Triangle Park, NC

Mar 80

U.S. Department of Commerce
National Technical Information Service
NTIS

ABMA	American Boiler Manufacturers Association	1500 Wilson Boulevard Arlington VA 22209	PB80-181266
DoE	United States Department of Energy	Division of Power Systems Energy Technology Branch Washington DC 20545	
EPA	U.S. Environmental Protection Agency Office of Research and Development	Industrial Environmental Research Laboratory Research Triangle Park NC 27711	EPA-600/7-80-064a March 1980

Field Tests of Industrial Stoker Coal-fired Boilers for Emissions Control and Efficiency Improvement - Site E

Interagency Energy/Environment R&D Program Report

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO.	2.	3. RECIPIENT'S ACCESSION NO.
EPA-600/7-80-064a		PB80-181266

4. TITLE AND SUBTITLE	5. REPORT DATE
Field Tests of Industrial Stoker Coal-fired Boilers for Emissions Control and Efficiency Improvement--Site E	March 1980
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S)	8. PERFORMING ORGANIZATION REPORT NO.
P. L. Langsjoen, J. O. Burlingame, and J. E. Gabrielson	
9. PERFORMING ORGANIZATION NAME AND ADDRESS	10. PROGRAM ELEMENT NO.
KVB, Inc. 6176 Olson Memorial Highway Minneapolis, Minnesota 55422	EHE624
	11. CONTRACT/GRANT NO. IAG-D7-E681 (EPA) and EF-77-C-01-2609 (DOE)
12. SPONSORING AGENCY NAME AND ADDRESS	13. TYPE OF REPORT AND PERIOD COVERED
EPA, Office of Research and Development* Industrial Environmental Research Laboratory Research Triangle Park, NC 27711	Final; 11/78-1/79
	14. SPONSORING AGENCY CODE EPA/600/13

15. SUPPLEMENTARY NOTES IERL-RTP project officer is R. E. Hall. (*) Cosponsors are DoE (W. T. Harvey Jr.) and the American Boiler Manufacturers Assoc. EPA-600/7-78-136a, -79-041a, -79-130a, and -79-237a are Site A, B, C, and D reports.

16. ABSTRACT The report gives results of field measurements made on a 180,000 lb/hr coal-fired spreader-stoker boiler. The effects of various parameters on boiler emissions and efficiency were studied. Parameters included overfire air, excess air, boiler load, and coal properties. Measurements included O2, CO2, CO, NO, NO2, SO2, SO3, controlled and uncontrolled particulate loading, particle size distribution of the uncontrolled flyash, and combustible content of the ash. In addition to test results and observations, the report describes the facility tested, coals fired, test equipment, and procedures. This unit was unique: it used paint oven exhaust gases as combustion air. Particulate loading on the unit averaged 5.51 lb/million Btu uncontrolled at high load. Nitric oxide emissions averaged 0.53 lb/million Btu at high load.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group	
Air Pollution	Improvement	Air Pollution Control	13B	
Boilers	Efficiency	Stationary Sources	13A	
Combustion	Flue Gases	Combustion Modification	21B	
Coal	Fly Ash	Spreader Stokers	21D	
Field Tests	Particle Size	Particulate	14B	
Dust	Nitrogen Oxides	Overfire Air	11G	07B
Stokers	Sulfur Oxides	Flyash Reinjection		

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS *(This Report)*	21. NO. OF PAGES
Release to Public	Unclassified	
	20. SECURITY CLASS *(This page)* Unclassified	22. PRICE

EPA Form 2220-1 (9-73)

EPA-600/7-80-064a

March 1980

Field Tests of Industrial Stoker Coal-fired Boilers for Emissions Control and Efficiency Improvement - Site E

by

P.L. Langsjoen, J.O. Burlingame, and J.E. Gabrielson

KVB, Inc.
6176 Olson Memorial Highway
Minneapolis, Minnesota 55422

IAG/Contract Nos. IAG-D7-E681 (EPA), EF-77-C-01-2609 (DoE)
Program Element No. EHE624

Project Officers: Robert E. Hall (EPA) and William T. Harvey, Jr. (DoE)

Industrial Environmental Research Laboratory
Office of Environmental Engineering and Technology
Research Triangle Park, NC 27711

Prepared for

U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Research and Development
Washington, DC 20460

U.S. DEPARTMENT OF ENERGY
Division of Power Systems/Energy Technology Branch
Washington, DC 20545
and

AMERICAN BOILER MANUFACTURERS ASSOCIATION
1500 Wilson Boulevard
Arlington, VA 22209

ACKNOWLEDGEMENTS

The authors wish to express their appreciation for the assistance and direction given the program by project monitors W. T. (Bill) Harvey of the United States Department of Energy (DOE) and R. E. (Bob) Hall of the United States Environmental Protection Agency (EPA). Thanks are due to their agencies, DOE and EPA, for co-funding the program.

We would also like to thank the American Boiler Manufacturers Association, ABMA Executive Director, W. H. (Bill) Axtman, ABMA's Project Manager, B. C. (Ben) Severs, and the members of the ABMA Stoker Technical Committee chaired by W. B. (Willard) McBurney of the McBurney Corporation for providing support through their time and travel to manage and review the program. The participating committee members listed alphabetically are as follows:

R. D. Bessette	Island Creek Coal Company
T. Davis	Combustion Engineering
N. H. Johnson	Detroit Stoker
K. Luuri	Riley Stoker
D. McCoy	E. Keeler Company
J. Mullan	National Coal Association
E. A. Nelson	Zurn Industries
E. Poitras	The McBurney Corporation
P. E. Ralston	Babcock and Wilcox
D. C. Reschley	Detroit Stoker
R. A. Santos	Zurn Industries

We would also like to recognize the KVB engineers and technicians who spent much time in the field, often under adverse conditions, testing the boilers and gathering data for this program. Those involved at Site E were Jim Burlingame, Russ Parker, Mike Jackson, and Jim Demont.

Finally, our gratitude goes to the host boiler facilities which invited us to test their boiler. At their request, the facilities will remain anonymous to protect their own interests. Without their cooperation and assistance this program would not have been possible.

TABLE OF CONTENTS

Section		Page
	ACKNOWLEDGEMENTS	ii
	LIST OF FIGURES	v
	LIST OF TABLES	vi
1.0	INTRODUCTION	1
2.0	EXECUTIVE SUMMARY	3
3.0	DESCRIPTION OF FACILITY TESTED AND COALS FIRED	9
	3.1 Boiler E Description	9
	3.2 Overfire Air System	9
	3.3 Particulate Collection Equipment	13
	3.4 Test Port Locations	13
	3.5 Coals Utilized	13
4.0	TEST EQUIPMENT AND PROCEDURES	17
	4.1 Gaseous Emissions Measurements (NOx, CO, CO_2, O_2, HC)	17
	4.1.1 Analytical Instruments and Related Equipment	17
	4.1.2 Recording Instruments	21
	4.1.3 Gas Sampling and Conditioning System	21
	4.1.4 Gaseous Emission Sampling Techniques	21
	4.2 Sulfur Oxides (SOx) Measurement and Procedures	23
	4.3 Particulate Measurement and Procedures	25
	4.4 Particle Size Distribution Measurement and Procedures	27
	4.5 Coal Sampling and Analysis Procedure	28
	4.6 Ash Collection and Analysis for Combustibles	30
	4.7 Boiler Efficiency Evaluation	31
	4.8 Trace Species Measurement	31
5.0	TEST RESULTS AND OBSERVATIONS	35
	5.1 Overfire Air	35
	5.1.1 Overfire Air Flow Rate Measurements	35
	5.1.2 Particulate Loading vs Overfire Air	37
	5.1.3 Nitric Oxide vs Overfire Air	41
	5.1.4 Boiler Efficiency vs Overfire Air	41
	5.2 Excess Oxygen and Grate Heat Release	44
	5.2.1 Excess Oxygen Operating Levels	44
	5.2.2 Particulate Loading vs Oxygen and Grate Heat Release	46
	5.2.3 Stack Opacity vs Oxygen and Grate Heat Release	48
	5.2.4 Nitric Oxide vs Oxygen and Grate Heat Release	50
	5.2.5 Carbon Monoxide vs Oxygen and Grate Heat Release	54
	5.2.6 Combustibles vs Oxygen and Grate Heat Release	64
	5.2.7 Boiler Efficiency vs Oxygen and Grate Heat Release	64

TABLE OF CONTENTS
(Continued)

Section		Page
5.3	Coal Properties	65
5.3.1	Chemical Composition of the Coals	67
5.3.2	Coal Size Consistency	72
5.3.3	Sulfur Balance	77
5.4	Particle Size Distribution of Flyash	77
5.5	Efficiency of Multiclone Dust Collector	83
5.6	Source Assessment Sampling System	83
	APPENDICES	91

LIST OF FIGURES

Figure No.		Page
3-1	Boiler E Schematic	12
3-2	Boiler E Sampling Plane Geometry	14
4-1	Flow Schematic of Mobile Flue Gas Monitoring Laboratory	22
4-2	SOx Sample Probe Construction	24
4-3	Sulfur Oxides Sampling Train (Shell-Emeryville)	24
4-4	EPA Method 5 Particulate Sampling Train	26
4-5	Brink Cascade Impactor Sampling Train Schematic	29
4-6	Source Assessment Sampling System (SASS) Flow Diagram	32
5-1	Pressure Flow Relationship, Overfire Air System	38
5-2	Particulate Loading Breakdown for Kentucky Coal as a Function of Overfire Air Conditions	39
5-3	Oxygen vs Grate Heat Release	45
5-4	Boiler Out Part. vs Grate Heat Release	47
5-5	Multiclone Out Part. vs Grate Heat Release	49
5-6	Stack Opacity vs Grate Heat Release	51
5-7	Stack Opacity vs Multiclone Out Part	52
5-8	Nitric Oxide vs Grate Heat Release	53
5-9	Nitric Oxide vs Oxygen	55
5-10	Nitric Oxide vs Oxygen	56
5-11	Nitric Oxide vs Oxygen	57
5-12	Nitric Oxide vs Oxygen	58
5-13	Trend in Nitric Oxide Emissions as a Function of Grate Heat Release (GHR) and Oxygen	59
5-14	Carbon Monoxide vs Grate Heat Release	60
5-15	Carbon Monoxide vs Oxygen	61
5-16	Boiler Out Comb vs Grate Heat Release	62
5-17	Bottom Ash Comb vs Grate Heat Release	63
5-18	Boiler Efficiency vs Grate Heat Release	66
5-19	Size Consistency of "As Fired" Kentucky Coal vs ABMA Recommended Sizing for Spreader Stokers	74
5-20	Size Consistency of "As Fired" Crushed Kentucky Coal vs ABMA Recommended Sizing for Spreader Stokers	75
5-21	Size Consistency of "As Fired" Eastern Kentucky Coal vs ABMA Recommended Sizing for Spreader Stokers	76
5-22	Particle Size Distribution at the Economizer Outlet from Brink Cascade Impactor Tests	81
5-23	Particle Size Distribution at the Boiler Outlet from SASS Cyclone Tests	82
5-24	Multiclone Eff vs Grate Heat Release	85

LIST OF TABLES

Table No.		Page
2-1	Emission Data Summary	8
3-1	Design Data	10
3-2	Predicted Performance	11
3-3	Average Coal Analysis	15
5-1	Overfire Air Flow Rates	36
5-2	Effect of Overfire Air on Emissions and Efficiency, Kentucky Coal	40
5-3	Nitric Oxide Emissions vs Overfire Air	42
5-4	Combustibles in Flyash vs Overfire Air	43
5-5	Ash Carryover vs Coal Type	48
5-6	Average Heat Losses by Coal Type	65
5-7	Coal Properties Corrected to a Constant 10^6Btu Basis	67
5-8	Fuel Analysis - Kentucky Coal	68
5-9	Fuel Analysis - Crushed Kentucky Coal	69
5-10	Fuel Analysis - Eastern Kentucky Coal	70
5-11	Mineral Analysis of Coal Ash	71
5-12	Relationship Between Coals Fired and Emissions	72
5-13	As Fired Coal Size Consistency	73
5-14	Sulfur Balance	78
5-15	Description of Particle Size Distribution Tests	79
5-16	Results of Particle Size Distribution Tests	80
5-17	Efficiency of Multiclone Dust Collector	84
5-18	Polynuclear Aromatic Hydrocarbons Sought in the Site E SASS samples	86
5-19	Particulate Emissions	87
5-20	Heat Losses and Efficiencies	88
5-21	Summary of Percent Combustibles in Refuse	89
5-22	Steam Flows and Heat Release Rates	90

1.0 INTRODUCTION

The principal objective of the test program described in this report, one of several reports in a series, is to produce information which will increase the ability of boiler manufacturers to design and fabricate stoker boilers that are an economical and environmentally satisfactory alternative to oil-fired units. Further objectives of the program are to: provide information to stoker boiler operators concerning the efficient operation of their boilers; provide assistance to stoker boiler operators in planning their coal supply contracts; refine application of existing pollution control equipment with special emphasis on performance; and contribute to the design of new pollution control equipment.

In order to meet these objectives, it is necessary to define stoker boiler designs which will provide efficient operation and minimum gaseous and particulate emissions, and define what those emissions are in order to facilitate preparation of attainable national emission standards for industrial size, coal-fired boilers. To do this, boiler emissions and efficiency must be measured as a function of coal analysis and sizing, rate of flyash reinjection, overfire admission, ash handling, grate size, and other variables for different boiler, furnace, and stoker designs.

A field test program designed to address the objectives outlined above was awarded to the American Boiler Manufacturers Association (ABMA), sponsored by the United States Department of Energy (DOE) under contract number EF-77-C-01-2609, and co-sponsored by the United States Environmental Protection Agency (EPA) under inter-agency agreement number IAG-D7-E681. The program is directed by an ABMA Stoker Technical Committee which, in turn, has subcontracted the field test portion to KVB, Inc., of Minneapolis, Minnesota.

This report is the Final Technical Report for the fifth of eleven boilers to be tested under the ABMA program. It contains a description of the facility tested, the coals fired, the test equipment and procedures, and the results and observations of testing. There is also a data supplement to this report containing the "raw" data sheets from the tests conducted. The data

supplement has the same EPA report number as this report except that it is followed by "b" rather than "a". As a compilation of all data obtained at this test site, the supplement acts as a research tool for further data reduction and analysis as new areas of interest are uncovered in subsequent testing.

At the completion of this program, a Final Technical Report will combine and correlate the test results from all sites tested. A report containing operating guidelines for boiler operators will also be written, along with a separate report covering trace species data. These reports will be available to interested parties through the NTIS or through the EPA's Technical Library.

Although it is EPA policy to use S.I. units in all EPA sponsored reports, an exception has been made herein because English units have been conventionally used to describe boiler design and operation. Conversion tables are provided in the Appendix for those who prefer S.I. units.

To protect the interest of the host boiler facilities, each test site in this program has been given a letter designation. As the fifth site tested, this is the Final Technical Report for Test Site E under the program entitled "A Testing Program to Update Equipment Specifications and Design Criteria for Stoker Fired Boilers."

2.0 EXECUTIVE SUMMARY

A spreader stoker rated at 180,000 lbs steam/hour was tested for emissions and efficiency between November 15, 1978, and January 19, 1979. This stoker was unique in that it had been recently retrofitted to use paint oven exhaust gases as combustion air. The paint oven exhaust gases contained between 14.5 and 20.5% oxygen. A side effect of this retrofit was a reduced steaming capacity. Maximum obtainable load during the period these tests were run was in the range 110-125 thousand pounds of steam per hour. This represents a 30% reduction in design capacity.

All but three of the tests run on this boiler used the paint oven exhaust gases as combustion air. The three tests run on ambient air resulted in similar emission levels and boiler efficiencies to those run on paint oven exhaust gases. The three ambient air tests are indicated on all plots in this report with solid symbols to differentiate them from tests run on paint oven exhaust gases.

Unfortunately, the test plan for Test Site E was not completed due to the unanticipated boiler loading limitations and the difficulty in obtaining ambient air test data. This section summarizes the results of those tests completed at Test Site E, and provides references to supporting figures, tables and commentary found in the main text of this report.

UNIT TESTED: Described in Section 3.0, pages 9-13.

- Riley Boiler
  - Built 1973
  - Type VOSP
  - 180,000 lb/hr rated capacity
  - 175 psig operating steam pressure
  - 427°F steam leaving superheater
  - Economizer
- Riley Spreader Stoker
  - Four overthrowing type feeders
  - Traveling grate with front ash discharge
  - Flyash reinjection from boiler hopper only
  - Two rows OFA jets on rear wall
  - One row OFA jets and one row underfeeder air jets on front wall

COALS TESTED: Individual coal analysis results given in Tables 5-8, 5-9, 5-10 and 5-11, pages 68-71. Commentary in Section 3.0, pages 13, 15. Coal analyses are summarized below.

0 Kentucky Coal

12,773 Btu/lb
8.52% Ash
0.86% Sulfur
6.13% Moisture
2700+°F Initial ash deformation temperature

0 Crushed Kentucky Coal

12,831 Btu/lb
9.08% Ash
0.71% Sulfur
5.69% Moisture
2700+°F Initial ash deformation temperature

0 Eastern Kentucky Coal

12,722 Btu/lb
8.21% Ash
0.78% Sulfur
6.31% Moisture
2700+°F Initial ash deformation temperature

OVERFIRE AIR TEST RESULTS: Overfire air (OFA) pressure was the independent variable on several tests. Normal operation is high pressure on the front upper, front lower and rear lower jets, and low pressure on the rear upper jets. Variations to the rear upper and lower OFA pressures were examined with the following results. (Section 5.1, pages 35-43.

0 Particulate Loading

Changing the rear overfire air pressures had no significant effect on particulate mass loading (Section 5.1.2, pages 37-41; Figure 5-2, page 39; Table 5-2, page 40.

0 Nitric Oxide

Changing the rear overfire air pressures had no significant effect on nitric oxide concentrations (Section 5.1.3, page 41; Table 5-3, page 42)

0 Boiler Efficiency

Changing the rear overfire air pressures had no significant effect on boiler efficiency (Section 5.1.4, page 41; Table 5-4, page 43.

BOILER EMISSION PROFILES: Boiler emissions were measured over the load range 46-73% of design capacity which corresponds to a grate heat release range of 274,000 to 604,000 Btu/hr-ft^2. Measured oxygen levels ranged from 3.9-10.0%. The range of values and trends of the various emissions are summarized below (Section 5.2, pages 44-65).

0 Excess Oxygen Operating Levels

The excess oxygen operating level was within the normal range for a spreader stoker. At 70% of design capacity the unit successfully operated at 5.9% O_2. In one test the unit was operated at 3.9% O_2 but the resulting particulate loading and opacity were excessive. The design excess air on this unit is 30%, or 5.3% O_2. The data indicates that this level could be easily met at design capacity (Section 5.2.1, pages 44-46, Figure 5-3, page 45).

0 Particulate Loading

Boiler outlet and dust collector outlet particulate loadings both showed an increasing trend with increasing grate heat release. At high grate heat release above 500x10^{3}Btu/hr-ft^2, boiler outlet particulate loadings averaged 5.51$\pm$0.66 lb/10^{6}Btu, and dust collector outlet particulate loadings averaged 1.90$\pm$1.49. Reducing the excess air to 3.9% O_2 resulted in excessively high particulate loadings of 6.5 lb/10^{6}Btu at the boiler outlet and 3.8 lb/10^{6}Btu at the dust collector outlet (Section 5.2.2, pages 46-48, Figures 5-4, 5-5, pages 47, 49).

0 Stack Opacity

Stack opacity was measured with a transmissometer which was not checked for calibration. Opacity readings ranged from 17 to 55%. Opacity showed no trend with grate heat release but did correlate with dust collector outlet particulate loading (Section 5.2.3, pages 48-50; Figures 5-6, 5-7, pages 51, 52).

0 Nitric Oxide

At high grate heat release, above 500x10^{3}Btu/hr-ft^2, nitric oxide (NO) averaged 0.533$\pm$0.047 lbs/10^{6}Btu and increased with increasing oxygen at a rate of 0.037 lbs/10^{6}Btu increase in NO for each one percent increase in O_2. There is some evidence that the paint oven exhaust gases produced higher NO levels than ambient air did (Section 5.2.4, pages 50-54; Figures 5-8 through 5-13, pages 53, 55-59).

0 Carbon Monoxide

Limited data shows that carbon monoxide (CO) concentrations were at insignificant levels of less than 150 ppm (0.015%). The data shows a decreasing trend in CO with increasing grate heat release. CO data was insufficient to establish any trend with oxygen. (Section 5.2.5, pages 54-61; Figures 5-14, 5-15, pages 60-62).

- Combustibles in Ash

  Combustibles in the boiler outlet flyash averaged 66% by weight and accounted for an average 4.4% heat loss. They showed an increasing trend with increasing grate heat release and were not affected by the change in combustion air composition. Combustibles in the bottom ash averaged ten percent by weight and accounted for an average 0.87% heat loss. Bottom ash combustibles were invariant with grate heat release and combustion air composition (Section 5.2.6, page 61; Figures 5-16, 5-17, pages 63-64).

BOILER EFFICIENCY: Boiler efficiency was determined for sixteen tests using the ASTM heat loss method. At high grate heat release, above 500×10^3 Btu/hr-ft^2, boiler efficiency averaged 79.88%. Design efficiency on the boiler was 80.41% based on Ohio coal. Boiler efficiency showed a decreasing trend with increasing grate heat release and was invariant with combustion air composition (Section 5.2.7, pages 61-65; Figure 5-18, page 66; Table 5-6, page 65; Table 5-20, page 88).

COAL PROPERTIES: Emissions and boiler efficiency were studied to determine any effects which could be related to differences in the properties of the three coals fired. Very few coal related differences were found due to the similarities of the three coals (Section 5.3, pages 65-77).

- Particulate Loading

  Crushed Kentucky coal showed the highest particulate loadings at the dust collector outlet. Coal was not a factor at the boiler outlet (Figure 5-5, page 49; Figure 5-4, page 47).

- Opacity

  Crushed Kentucky coal showed the highest opacity of the three coals (Figure 5-6, page 51).

- Nitric Oxide

  Crushed Kentucky coal had the highest NO, East Kentucky coal had the lowest NO (Figure 5-8, page 53).

- Combustibles in Ash

  East Kentucky coal had the lowest combustible level in the boiler outlet flyash. Coal was not a factor in bottom ash combustibles (Figures 5-16, 5-17, pages 63-64).

- Boiler Efficiency

  No correlation found.

PARTICLE SIZE DISTRIBUTION: Size distribution of the flyash was measured twice at the boiler outlet using SASS cyclones, and twice at the economizer outlet using a Brink Cascade Impactor. In general, test results show that ten percent of the boiler outlet flyash was below 3 μm in diameter, and 25% was below 10 μm. (Section 5.4, pages 77-83; Tables 5-15, 5-16, pages 79-80; Figures 5-22, 5-23, pages 81, 82.)

EFFICIENCY OF MULTICLONE DUST COLLECTOR: Dust collector efficiency was determined in thirteen tests. Apparent plugging of the collector tubes resulted in a deterioration of collection efficiency with time. Efficiency averaged 87% during the first month of testing and 55% during the second month. Design efficiency of the collector was 96% based on a dust loading of 15% under 10 μm. (Section 5.5, page 83; Table 5-17, page 84; Figure 5-24, page 85.)

SOURCE ASSESSMENT SAMPLING SYSTEM: Flue gas was sampled for polynuclear aromatic hydrocarbons and trace elements during one test on Kentucky coal and one test on Eastern Kentucky coal. Data from these tests will be presented in a separate report at the completion of this test program. (Section 5.6, page 83; Table 5-18, page 86.)

The emissions data are summarized in Table 2-1 on the following page. Other data tables are included at the end of Section 5.0, Test Results and Observations. For reference, a Data Supplement containing all the unreduced data obtained at Site E is available under separate cover but with the same title followed by the words "Data Supplement," and having the same EPA document number followed by the letter "b" rather than "a". Copies of this report and the Data Supplement are available through EPA and NTIS.

TABLE 2-1. EMISSION DATA SUMMARY - TEST SITE E

Test No.	Date	% Design Capacity[4]	Coal	% O_2 in[1] Comb Air	Test Description	Excess Air %	O_2 %	CO_2 %	CO ppm	NO ppm	NO lb/10^6Btu	NO_2[2] lb/10^6Btu	Boiler Out Part lb/10^6Btu	D.C. Out Part lb/10^6Btu	Stack Opacity %
02	11/16/78	61	Ky	16.6	Baseline	52	7.6	12.0	81	480	0.645	--	3.464	2.966[3]	24
03	11/18/78	46	Ky	20.9	Low Load-Amb Air	67	8.8	11.1	100	372	0.500	--	2.960	0.313	34
04	11/20/78	73	Ky	16.3	Maximum Load	47	7.2	12.5	38	421	0.566	--	4.972	0.198	28
05	11/21/78	62	Ky	15.7	Medium Load	83	9.9	9.7	83	477	0.641	--	6.188	0.271	20
06	12/12/78	65	Ky	14.7	Low RU, RL OFA	70	9.0	11.7	62	456	0.614	--	2.060	0.335	17
07	12/13/78	67	Ky	19.6	Low FL, RL OFA	29	5.2	13.9	147	367	0.494	0.000	5.230	1.824	45
08	12/15/78	61	Ky	20.3	High Balanced OFA	43	6.8	12.5	OOS	367	0.493	-0.005	4.493	0.190	38
09	12/16/78	57	Ky	20.9	Med Load-Amb Air	53	7.7	11.6	OOS	368	0.496	-0.001	3.984	0.641	32
10a	12/17/78	61	Ky	--	Vary OFA-Baseline	53	7.7	11.4	OOS	424	0.571	--	--	--	25
10b	12/17/78	61	Ky	--	-Low RU	52	7.6	11.6	OOS	404	0.544	--	--	--	25
10c	12/17/78	61	Ky	--	-High Balanced	85	10.0	9.9	OOS	439	0.591	--	--	--	25
10d	12/17/78	61	Ky	--	-Low RL	59	8.2	11.1	OOS	423	0.570	--	--	--	25
10e	12/17/78	61	Ky	--	-Low Balanced	60	8.3	11.3	OOS	435	0.481	--	--	--	25
11	12/18/78	62	Ky	19.9	Low Rear OFA	40	6.5	12.9	OOS	357	0.480	--	4.316	1.558	46
12	12/20/78	65	Cr Ky	19.9	Baseline	35	5.9	12.9	OOS	393	0.528	-0.003	3.509	1.852	33
13	12/20/78	48	Cr Ky	19.9	Low Load	73	9.2	10.1	OOS	483	0.650	-0.001	3.631	1.460	45
14	12/20/78	69	Cr Ky	18.7	High Load	19	3.9	14.5	OOS	454	0.610	--	6.469	3.843	55
15	1/05/79	70	East Ky	20.4	Baseline	35	5.9	13.5	OOS	385	0.518	0.000	5.380	1.746	38
16	1/08/79	62	East Ky	19.7	SASS-SOx	60	8.3	11.0	OOS	360	0.486	--	--	--	31
17	1/10/79	62	Ky	19.5	SASS-SOx	37	6.2	13.4	OOS	389	0.524	--	--	--	48
18a	1/12/79	65	Ky	--	Vary O_2 -Low	62	8.4	11.2	OOS	358	0.482	--	--	--	33
18b	1/12/79	65	Ky	--	-Medium	70	9.0	10.6	OOS	421	0.567	--	--	--	33
18c	1/12/79	65	Ky	--	-High	82	9.8	10.0	OOS	435	0.586	--	--	--	33
18d	1/12/79	65	Ky	--	-Medium	74	9.3	10.0	OOS	428	0.576	--	--	--	33
19	1/17/79	--	--	--	OFA Velocity	--	--	--	OOS	--	--	--	--	--	--
20	1/18/79	63	Ky	20.9	High Load-Amb Air	45	7.0	12.3	OOS	405	0.545	--	0.785	2.408	43

[1]Paint oven exhaust fumes used on all but three tests, Test Nos. 3, 9, 20 used ambient air.

[2]The negative NO_2 concentrations result from limitations to instruments resolution and may be considered as zero readings.

[3]Test No. 2 particulates were measured at boiler outlet and economizer outlet. All other particulate tests were at boiler outlet and dust collector outlet.

[4]Maximum obtainable load was restricted to 73% of design capacity due to retrofit combustion air system.

-- means data not obtained; OOS means instrument out of service.

3.0 DESCRIPTION OF FACILITY TESTED AND COALS FIRED

This section discusses the general physical layout and operational characteristics of the boiler tested at Test Site E. The coals utilized in this test series are also discussed.

3.1 BOILER E DESCRIPTION

Boiler E is a Riley (VOSP) unit, designed for 250 psig, and capable of a maximum continuous capacity of 180,000 pounds of steam per hour at 175 psig and a final superheated steam temperature of 427°F using feedwater at 220°F. The unit has a Riley Stoker Company traveling grate spreader stoker, with a front end ash discharge. Undergrate air utilizes paint oven exhaust gases. Design data on the boiler and stoker are presented in Table 3-1. Predicted performance data are given in Table 3-2. A side elevation of the boiler is shown in Figure 3-1.

The boiler is equipped with a Western Precipitator multiclone dust collector. The collector has a predicted collection efficiency of 96%, assuming that 15% of the particles are under ten micrometers.

3.2 OVERFIRE AIR SYSTEM

The overfire air system on Boiler E consists of two rows of air jets on the back wall and two rows of jets on the front wall. The configuration of the overfire air system is described below:

Front Upper Row:	8 jets 6' 6" above grate 15° below horizontal
Rear Upper Row:	8 jets 6' 0" above grate Horizontal
Rear Lower Row:	8 jets 2' 0" above grate Horizontal

TABLE 3-1

DESIGN DATA
TEST SITE E

BOILER:	Type	Riley (VOSP) Boiler
	Boiler Heating Surface	13,639 ft^2
	Water Wall Heating Surface	2,551 ft^2
	Design Pressure	250 psi
	Tube Diameter	3.5"
SUPERHEATER:	Heating Surface	480 ft^2
	No. of Steam Passes	1
ECONOMIZER:	Type	Tube
	Heating Surface	6,350 ft^2
FURNACE	Volume	10,255 ft^3
	Width (centerline to centerline waterwall tubes)	16'11-3/4"
	Depth (front to back)	21'06-3/8"
	Height (mean)	32' 0"
STOKER:	Stoker Type	Riley Spreader (4 feeders)
	Grate Type	Traveling (front discharge)
	Grate Width	16'0"
	Grate Length	23'0"
	Effective Grate Area	344 ft^2
HEAT RATES:	Maximum Continuous Steam Capacity	180,000 lbs/hr
	Input to Furnace	232x10^6Btu/hr

TABLE 3-2

PREDICTED PERFORMANCE
TEST SITE E

Steam Leaving Superheater	180,000 lbs/hr
Fuel	Ohio Coal *
Excess Air Leaving Boiler	30%
Coal Flow	21,100 lbs/hr
Flue Gas Leaving Boiler	247,000 lbs/hr
Steam Pressure at SH Outlet	175 psig
Economizer to Drum Pressure Drop	20 psig
Temperature Steam Leaving Superheater	427°F
Temperature Flue Gas Leaving Boiler	600°F
Temperature Flue Gas Leaving Economizer	350°F
Temperature Water Entering Economizer	220°F
Temperature Water Leaving Economizer	310°F
Furnace Draft Loss	0.15 "H_2O
Boiler Draft Loss	1.08 "H_2O
Economizer Draft Loss	3.94 "H_2O
Damper and Duct Draft Loss	0.77 "H_2O
Dust Collector Draft Loss	2.96 "H_2O
Total Draft Loss	8.90 "H_2O
Dry Gas Heat Loss	6.55 %
H_2O and H_2 in Fuel Heat Loss	5.18 %
Moisture in Air Heat Loss	0.16 %
Unburned Combustible Heat Loss	5.80 %
Radiation Heat Loss	0.40 %
Unaccounted for and Manufacturers Margin	1.50 %
Total Heat Loss	19.59 %
Efficiency of Unit	80.41 %

*Predicted performance is based on combustion air entering at 80°F and coal fuel containing 10% moisture, 2.5% sulfur, 4.5% H_2, 1.2% N_2, 62.2% C, 7.6% O_2, 12% ash.

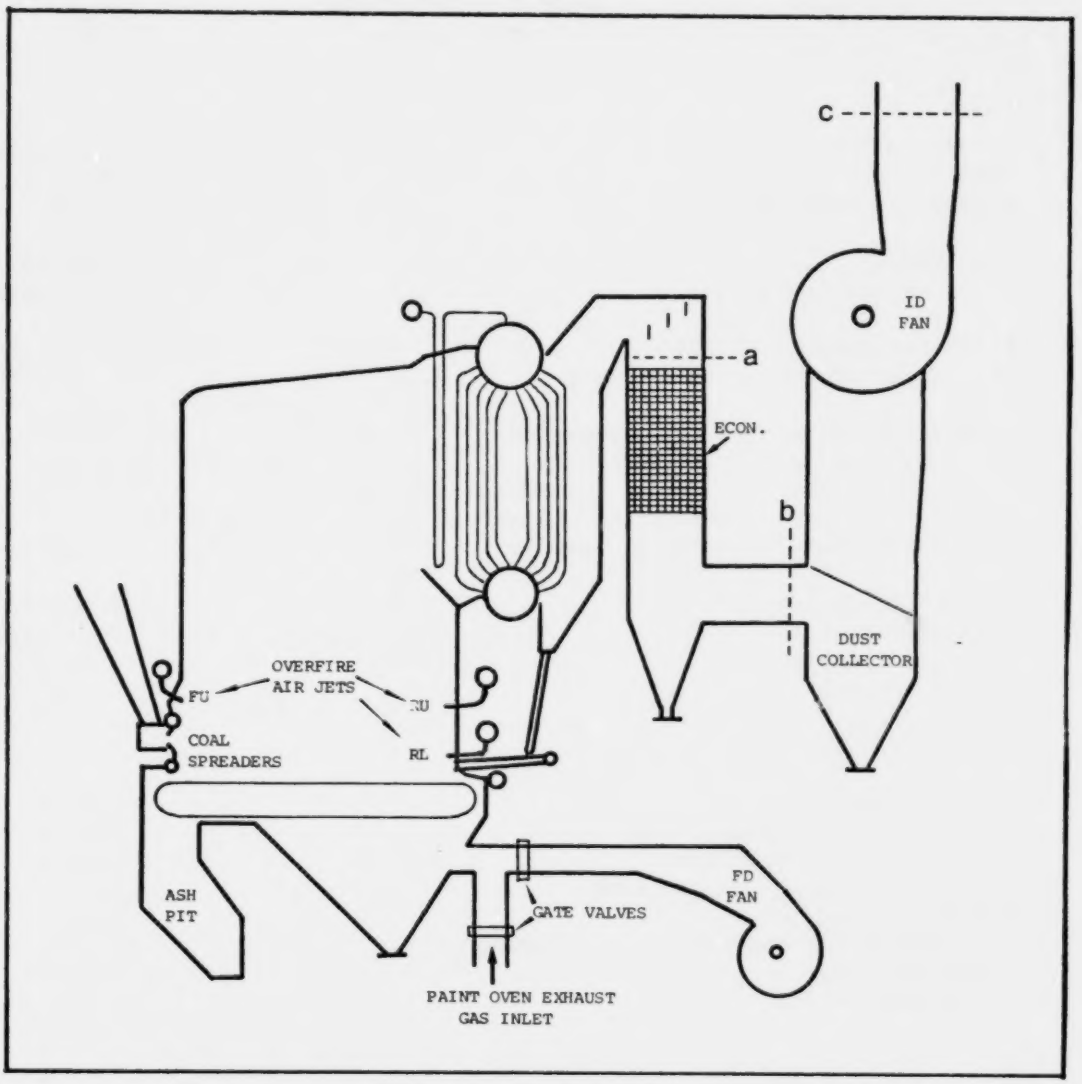


Figure 3-1. Boiler E Schematic

a - Boiler Outlet Sampling Plane
b - Economizer Outlet Sampling Plane
c - Dust Collector Outlet Sampling Plane

Rear Lower Row:	8 jets 2'0" above grate Horizontal

3.3 PARTICULATE COLLECTION EQUIPMENT

The boiler is equipped with a Western Precipitator multiclone dust collector. The multiclone's collection efficiency deteriorated during the testing period, probably due to dust buildup.

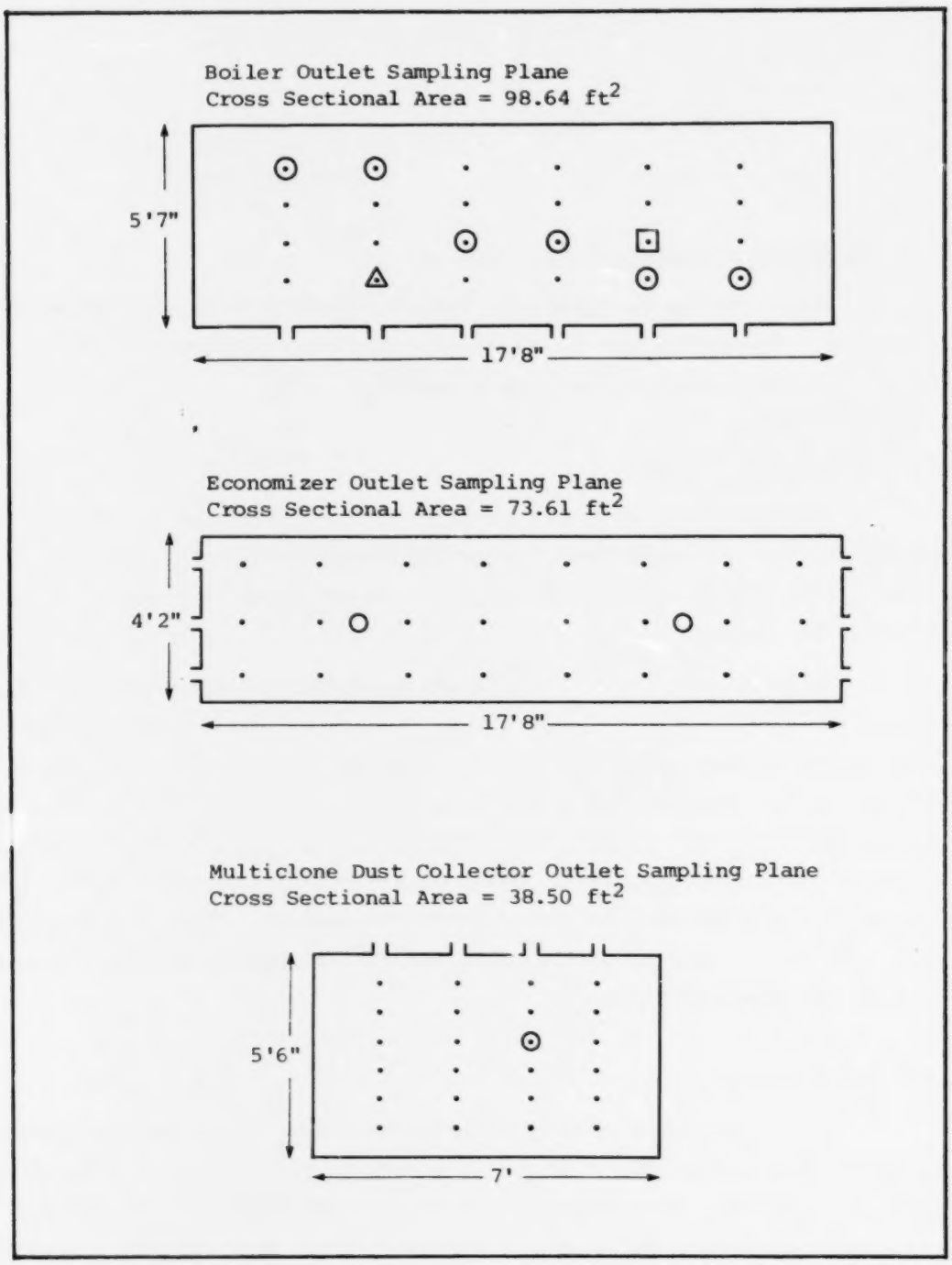
3.4 TEST PORT LOCATIONS

Emissions measurements were made at three locations -- at the boiler outlet (before the economizer), after the economizer, and at the dust collector outlet. The locations of these sample sites are shown in Figure 3-1. Their geometry is shown in Figure 3-2.

Whenever particulate loading was measured it was measured simultaneously at both locations using 24-point sample traverses. Gaseous measurements of O_2, CO_2, CO and NO were obtained by pulling samples individually and compositely from six probes distributed along the width of the boiler outlet duct. SOx measurements and SASS samples for organic and trace element determinations were each obtained from single points within the boiler outlet duct. A heated sample line was attached to one of the middle gaseous probes at the boiler outlet. Its purpose was to eliminate losses due to condensation when measuring NO_2 and unburned hydrocarbons.

3.5 COALS UTILIZED

Three coal types were fired at Test Site E. These were an Eastern Kentucky coal, a Kentucky coal and a crushed Kentucky coal. Coal samples were taken for each test involving particulate or SASS sampling. The average analyses obtained from these samples are presented in Table 3-3. The analyses show that the three coals are quite similar in their composition, based on both proximate and ultimate analyses. The analyses of each individual coal sample are presented in Section 5.0, Test Results and Observations, Tables 5-7 through 5-10.



• Particulate Sampling Points
○ Gaseous Sampling Points
△ SOx
□ SASS

Figure 3-2. Boiler E Sampling Plane Geometry

TABLE 3-3

AVERAGE COAL ANALYSIS
TEST SITE E

	Kentucky Coal	Crushed Kentucky Coal	East Kentucky Coal
PROXIMATE (As Rec'd)			
% Moisture	6.13	5.69	6.31
% Ash	8.52	9.08	8.21
% Volatile	35.06	33.50	34.47
% Fixed Carbon	50.29	51.73	51.02
Btu/lb	12773	12831	12722
% Sulfur	0.86	0.71	0.78
ULTIMATE (As Rec'd)			
% Moisture	6.13	5.69	6.31
% Carbon	71.69	71.95	71.31
% Hydrogen	4.73	4.72	4.70
% Nitrogen	1.30	1.36	1.13
% Chlorine	0.13	0.14	0.08
% Sulfur	0.86	0.71	0.78
% Ash	8.52	9.08	8.21
% Oxygen (Diff)	6.67	6.36	7.50

4.0 TEST EQUIPMENT AND PROCEDURES

This section details how specific emissions were measured and the sampling procedures followed to assure that accurate, reliable data were collected.

4.1 GASEOUS EMISSIONS MEASUREMENTS (NOx, CO, CO_2, O_2, HC)

A description is given below of the analytical instrumentation, related equipment, and the gas sampling and conditioning system, all of which are located in a mobile testing van owned and operated by KVB. The systems have been developed as a result of testing since 1970, and are operational and fully checked out.

4.1.1 Analytical Instruments and Related Equipment

The analytical system consists of five instruments and associated equipment for simultaneously measuring the constituents of flue gas. The analyzers, recorders, valves, controls, and manifolds are mounted on a panel in the vehicle. The analyzers are shock mounted to prevent vibration damage. The flue gas constituents which are measured are oxides of nitrogen (NO, NOx), carbon monoxide (CO), carbon dioxide (CO_2), oxygen (O_2), and gaseous hydrocarbons (HC).

Listed below are the measurement parameters, the analyzer model furnished, and the range and accuracy of each parameter for the system. A detailed discussion of each analyzer follows:

Constituent:	Nitric Oxide/Total Oxides of Nitrogen (NO/NOx)
Analyzer:	Thermo Electron Model 10 Chemiluminescent Analyzer
Range:	0-2.5, 10, 25, 100, 250, 1000, 2500, 10,000 ppm NO
Accuracy:	±1% of full scale

Constituent:	Carbon Monoxide
Analyzer:	Beckman Model 315B NDIR Analyzer
Range:	0-500 and 0-2000 ppm CO
Accuracy:	±1% of full scale

Preceding page blank

Constituent: Carbon Dioxide
Analyzer: Beckman Model 864 NDIR Analyzer
Range: 0-5% and 0-20% CO_2
Accuracy: ±1% of full scale

Constituent: Oxygen
Analyzer: Teledyne Model 326A Fuel Cell Analyzer
Range: 0-5, 10, and 25% O_2 full scale
Accuracy: ±1% of full scale

Constituent: Hydrocarbons
Analyzer: Beckman Model 402 Flame Ionization Analyzer
Range: 5 ppm full scale to 10% full scale
Accuracy: ±1% of full scale

Oxides of nitrogen. The instrument used to monitor oxides of nitrogen is a Thermo Electron chemiluminescent nitric oxide analyzer. The instrument operates by measuring the chemiluminescent reaction of NO and O_3 to form NO_2. Light is emitted when electronically excited NO_2 molecules revert to their ground state. The resulting chemiluminescence is monitored through an optical filter by a high sensitivity photomultiplier, the output of which is linearly proportional to the NO concentration.

Air for the ozonator is drawn from ambient air through a dryer and a ten micrometer filter element. Flow control for the instrument is accomplished by means of a small bellows pump mounted on the vent of the instrument downstream of a separator that prevents water from collecting in the pump.

The basic analyzer is sensitive only to NO molecules. To measure NOx (i.e., $NO+NO_2$), the NO_2 is first converted to NO. This is accomplished by a converter which is included with the analyzer. The conversion occurs as the gas passes through a thermally insulated, resistance heated, stainless steel coil. With the application of heat, NO_2 molecules in the sample gas are reduced to NO molecules, and the analyzer now reads NOx. NO_2 is obtained by the difference in readings obtained with and without the converter in operation.

Specifications: Accuracy 1% of full scale
Span stability ±1% of full scale in 24 hours
Zero stability ±1 ppm in 24 hours
Power requirements 115±10V, 60 Hz, 1000 watts
Response 90% of full scale in 1 sec. (NOx mode),
0.7 sec. NO mode
Output 4-20 ma

Sensitivity 0.5 ppm
Linearity ±1% of full scale
Vacuum detector operation
Range: 2.5, 10, 25, 100, 250, 1000, 2500, 10,000 ppm full scale

Carbon monoxide. Carbon monoxide concentration is measured by a Beckman 315B non-dispersive infrared analyzer. This instrument measures the differential in infrared energy absorbed from energy beams passed through a reference cell (containing a gas selected to have minimal absorption of infrared energy in the wavelength absorbed by the gas component of interest) and a sample cell through which the sample gas flows continuously. The differential absorption appears as a reading on a scale from 0 to 100 and is then related to the concentration of the specie of interest by calibration curves supplied with the instrument. The operating ranges for the CO analyzer are 0-500 ppm and 0-2000 ppm.

Specifications:
Span stability ±1% of full scale in 24 hours
Zero stability ±1% of full scale in 24 hours
Ambient temperature range 32°F to 120°F
Line voltage 115±15V rms
Response 90% of full scale in 0.5 or 2.5 sec.
Precision ±1% of full scale
Output 4-20 ma

Carbon dioxide. Carbon dioxide concentration is measured by a Beckman Model 864 short path-length, non-dispersive infrared analyzer. This instrument measures the differential in infrared energy absorbed from energy beams passed through a reference cell (containing a gas selected to have minimal absorption of infrared energy in the wavelength absorbed by the gas component of interest) and a sample cell through which the sample gas flows continuously. The differential absorption appears as a reading on a scale from 0 to 100 and is then related to the concentration of the specie of interest by calibration curves supplied with the instrument. The operating ranges for the CO_2 analyzer are 0-5% and 0-20%.

Specifications:
Span stability ±1% of full scale in 24 hours
Zero stability ±1% of full scale in 24 hours
Ambient temperature range 32°F to 120°F
Line voltage 115±15V rms
Response 90% of full scale in 0.5 or 2.5 sec.
Precision ±1% of full scale
Output 4-20 ma

Oxygen. The oxygen content of the flue gas sample is automatically and continuously determined with a Teledyne Model 326A Oxygen analyzer. Oxygen in the flue gas diffuses through a Teflon membrane and is reduced on the surface of the cathode. A corresponding oxidation occurs at the anode internally and an electric current is produced that is proportional to the concentration of oxygen. This current is measured and conditioned by the instrument's electronic circuitry to give a final output in percent O_2 by volume for operating ranges of 0% to 5%, 0% to 10%, or 0% to 25%.

Specifications: Precision ±1% of full scale
Response 90% in less than 40 sec.
Sensitivity 1% of low range
Linearity ±1% of full scale
Ambient temperature range 32-125°F
Fuel cell life expectancy 40,000%-hours
Power requirement 115 VAC, 50-60 Hz, 100 watts
Output 4-20 ma

Hydrocarbons. Hydrocarbons are measured using a Beckman Model 402 hydrocarbon analyzer which utilizes the flame ionization method of detection. The sample is drawn to the analyzer through a heated line to prevent the loss of higher molecular weight hydrocarbons. It is then filtered and supplied to the burner by means of a pump and flow control system. The sensor, which is the burner, has its flame sustained by regulated flows of fuel (40% hydrogen plus 60% helium) and air. In the flame, the hydrocarbon components of the sample undergo a complete ionization that produces electrons and positive ions. Polarized electrodes collect these ions, causing a small current to flow through a circuit. This ionization current is proportional to the concentration of hydrocarbon atoms which enter the burner. The instrument is available with range selection from 5 ppm to 10% full scale as CH_4.

Specifications: Full scale sensitivity, adjustable from 5 ppm CH_4 to 10% CH_4
Ranges: Range multiplier switch has 8 positions: X1, X5, X10, X50, X100, X500, X1000, and X5000. In addition, span control provides continuously variable adjustment within a dynamic range of 10:1
Response time 90% full scale in 0.5 sec.
Precision ±1% of full scale
Electronic stability ±1% of full scale for successive identical samples

Reproducibility ±1% of full scale for successive identical samples
Analysis temperature: ambient
Ambient temperature 32°F to 110°F
Output 4-20 ma
Air requirements 350 to 400 cc/min of clean, hydrocarbon-free air, supplied at 30 to 200 psig
Fuel gas requirements 75 to 80 cc/min of pre-mixed fuel consisting of 40% hydrogen and 60% nitrogen or helium, supplied at 30 to 200 psig
Electrical power requirements 120V, 60 Hz
Automatic flame-out indication and fuel shut-off valve

4.1.2 Recording Instruments

The output of the four analyzers is displayed on front panel meters and are simultaneously recorded on a Texas Instrument Model FL04W6D four-pen strip chart recorder. The recorder specifications are as follows:

Chart size 9-3/4 inch
Accuracy ±0.25%
Linearity <0.1%
Line voltage 120V±10% at 60 Hz
Span step response: one second

4.1.3 Gas Sampling and Conditioning System

The gas sampling and conditioning system consists of probes, sample lines, valves, pumps, filters and other components necessary to deliver a representative, conditioned sample gas to the analytical instrumentation. The following sections describe the system and its components. The entire gas sampling and conditioning system shown schematically in Figure 4-1 is contained in the emission test vehicle.

4.1.4 Gaseous Emission Sampling Techniques

Boiler access points for gaseous sampling are selected in the same sample plane as are particulate sample points. Each probe consists of one-half inch 316 stainless steel heavy wall tubing. A 100 micrometer Mott Metallurgical Corporation sintered stainless steel filter is attached to each probe for removal of particulate material.

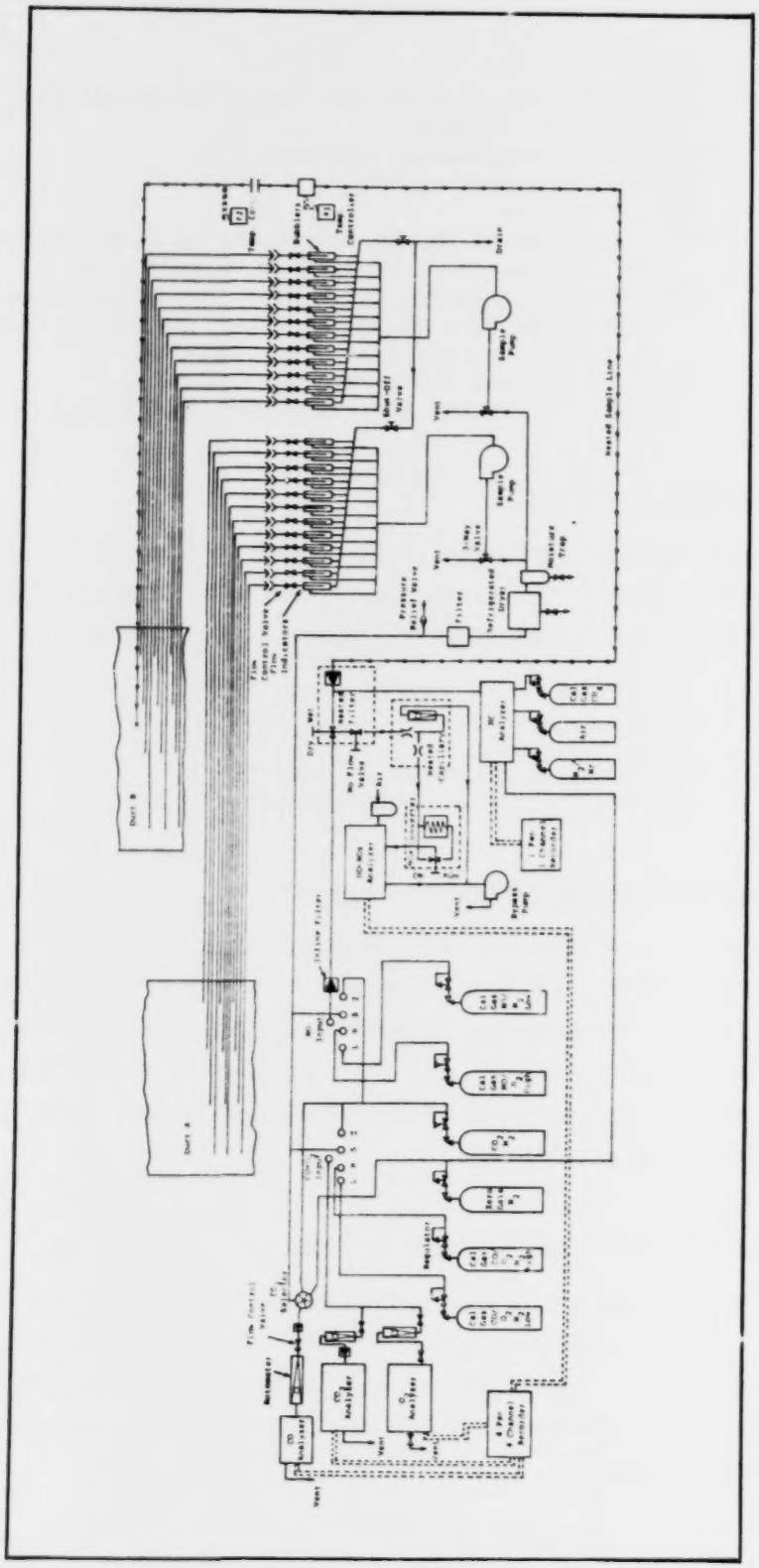


Figure 4-1. Flow Schematic of Mobile Flue Gas Monitoring Laboratory

Gas samples to be analyzed for O_2, CO_2, CO and NO are conveyed to the KVB mobile laboratory through 3/8 inch nylon sample lines, After passing through bubblers for flow control, the samples pass through a diaphragm pump and a refrigerated dryer to reduce the sample dew point temperature to 35°F. After the dryer, the sample gas is split between the various continuous gas monitors for analysis. Flow through each continuous monitor is accurately controlled with rotometers. Excess flow is vented to the outside. Gas samples may be drawn both individually and/or compositely from all probes during each test. The average emission values are reported in this report.

4.2 SULFUR OXIDES (SOx) MEASUREMENT AND PROCEDURES

Measurement of SO_2 and SO_3 concentrations is made by wet chemical analysis using both the "Shell-Emeryville" method and EPA Method 6. In the Shell-Emeryville method the gas sample is drawn from the stack through a glass probe (Figure 4-2), containing a quartz wool filter to remove particulate matter, into a system of three sintered glass plate absorbers (Figure 4-3). The first two absorbers contain aqueous isopropyl alcohol and remove the sulfur trioxide; the third contains aqueous hydrogen peroxide solution which absorbs the sulfur dioxide. Some of the sulfur trioxide is removed by the first absorber, while the remainder, which passes through as sulfuric acid mist, is completely removed by the secondary absorber mounted above the first. After the gas sample has passed through the absorbers, the gas train is purged with nitrogen to transfer sulfur dioxide, which has dissolved in the first two absorbers, to the third absorber to complete the separation of the two components. The isoprophy alcohol is used to inhibit the oxidation of sulfur dioxide to sulfur trioxide before it gets to the third absorber.

The isopropyl alcohol absorber solutions are combined and the sulfate resulting from the sulfur trioxide absorption is titrated with standard lead perchlorate solution using Sulfonazo III indicator. In a similar manner, the hydrogen peroxide solution is titrated for the sulfate resulting from the sulfur dioxide absorption.

The gas sample is drawn from the flue by a single probe made of quartz glass inserted into the duct approximately one-third to one-half way.

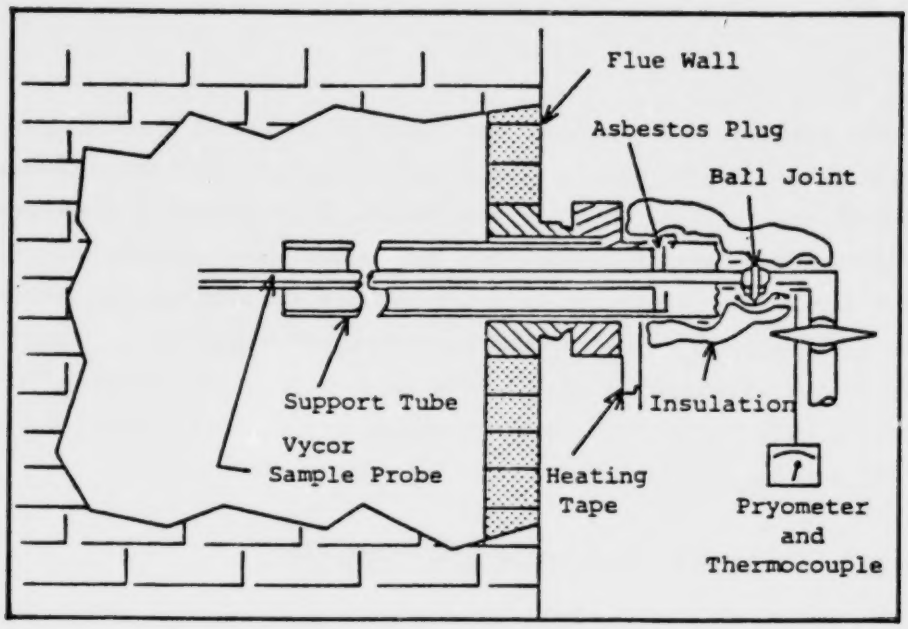


Figure 4-2. SOx Sample Probe Construction

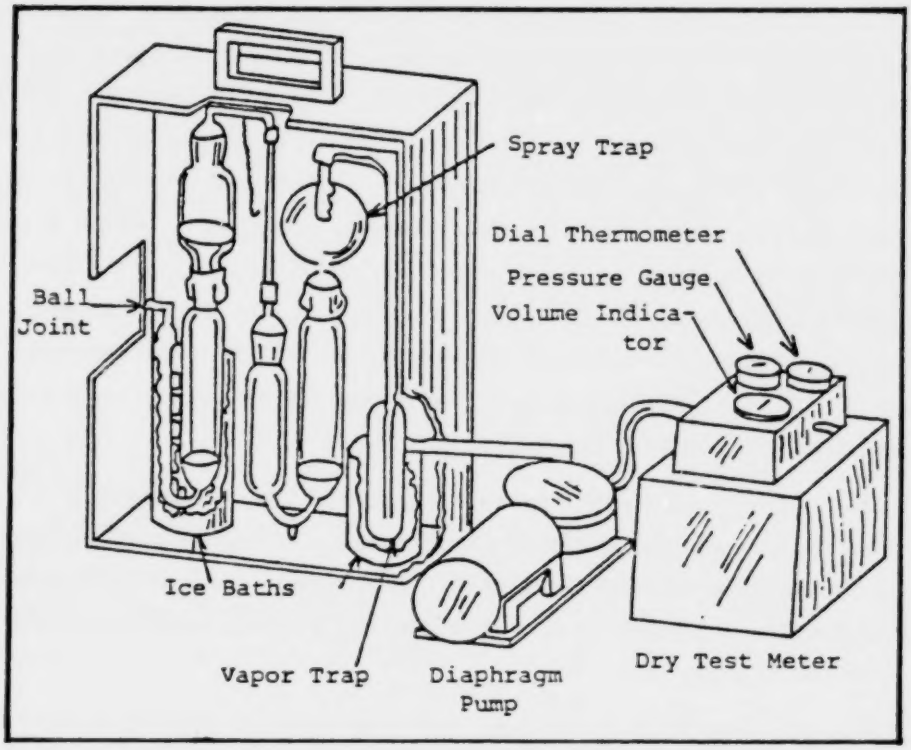


Figure 4-3. Sulfur Oxides Sampling Train
(Shell-Emeryville)

The inlet end of the probe holds a quartz wool filter to remove particulate matter. It is important that the entire probe temperature be kept above the dew point of sulfuric acid during sampling (minimum temperature of 260°C). This is accomplished by wrapping the probe with a heating tape.

EPA Method 6, which is an alternative method for determining SO_2, employs an impinger train consisting of a bubbler and three midget impingers. The bubbler contains isopropanol. The first and second impingers contain aqueous hydrogen peroxide. The third impinger is left dry. The quartz probe and filter used in the Shell-Emeryville method is also used in Method 6.

Method 6 differs from Shell-Emeryville in that Method 6 requires that the sample rate be proportional to stack gas velocity. Method 6 also differs from Shell-Emeryville in that the sample train in Method 6 is purged with ambient air, instead of nitrogen. Sample recovery involves combining the solutions from the first and second impingers. A 10 ml. aliquot of this solution is then titrated with standardized barium perchlorate.

Three repetitions of SOx sampling are made at each test point.

4.3 PARTICULATE MEASUREMENT AND PROCEDURES

Particulate samples are taken at the same sample ports as the gaseous emission samples using a Joy Manufacturing Company portable effluent sampler (Figure 4-4). This system, which meets the EPA design specifications for Test Method 5, Determination of Particulate Emissions from Stationary Sources (Federal Register, Volume 36, No. 27, page 24888, December 23, 1971), is used to perform both the initial velocity traverse and the particulate sample collection. Dry particulates are collected in a heated case using first a cyclone to separate particles larger than five micrometers and a 100 mm glass fiber filter for retention of particles down to 0.3 micrometers. Condensible particulates are collected in a train of four Greenburg-Smith impingers in an ice water bath. The control unit includes a total gas meter and thermocouple indicator. A pitot tube system is provided for setting sample flows to obtain isokinetic sampling conditions.

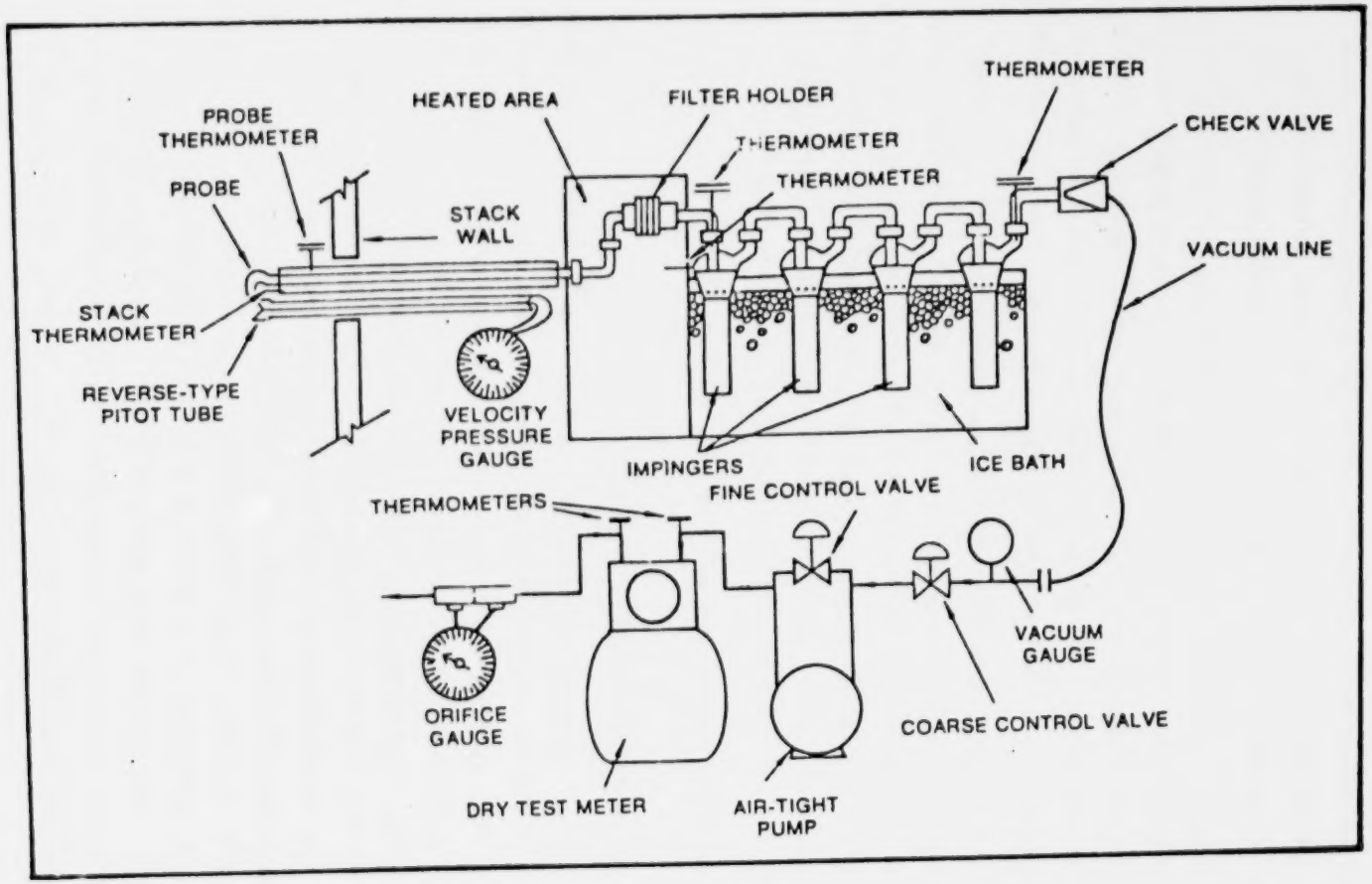


Figure 4-4. EPA Method 5 Particulate Sampling Train

All peripheral equipment is carried in the instrument van. This includes a scale (accurate to $\pm$0.1 mg), hot plate, drying oven (212°F), high temperature oven, desiccator, and related glassware. A particulate analysis laboratory is set up in the vicinity of the boiler in a vibration-free area. Here filters are prepared, tare weighed and weighed again after particulate collection. Also, probe washes are evaporated and weighed in the lab.

4.4 PARTICLE SIZE DISTRIBUTION MEASUREMENT AND PROCEDURES

Particle size distribution is measured using several methods. These include the Brink Cascade Impactor and the SASS cyclones. No Bahco samples were taken at this site. Each of these particle sizing methods has its advantages and disadvantages as described below.

Brink. The Brink cascade impactor is an in-situ particle sizing device which separates the particles into six size classifications. It has the advantage of collecting the entire sample. That is, everything down to the collection efficiency of the final filter is included in the analysis. It has, however, some disadvantages. If the particulate matter is spatially stratified within the duct, the single-point Brink sampler will yield erroneous results. Unfortunately, the particles at the outlets of stoker boilers may be considerably stratified. Another disadvantage is the instrument's small classification range (0.3 to 3.0 micrometers) and its small sample nozzle (1.5 to 2.0 mm maximum diameter). The particles being collected at the boiler outlet are often as large as the sample nozzle.

The sampling procedure is straight forward. First, the gas velocity at the sample point is determined using a calibrated S-type pitot tube. For this purpose a hand held particulate probe, inclined manometer, thermocouple and indicator are used. Second, a nozzle size is selected which will maintain isokinetic flow rates within the recommended .02-.07 ft^3/min rate at stack conditions. Having selected a nozzle and determined the required flow rate for isokinetics, the operating pressure drop across the impactor is determined from a calibration curve. This pressure drop is corrected for temperature, pressure and molecular weight of the gas to be sampled.

A sample is drawn at the predetermined ΔP for a time period which is dictated by mass loading and size distribution. To minimize weighing errors, it is desirable to collect several milligrams on each stage. However, to minimize reentrainment, a rule of thumb is that no stage should be loaded above 10 mg. A schematic of the Brink sampling train is shown in Figure 4-5.

SASS. The Source Assessment Sampling System (SASS) was not designed principally as a particle sizer but it includes three calibrated cyclones which can be used as such. The SASS train is a single point in-situ sampler. Thus, it is on a par with cascade impactors. Because it is a high volume sampler and samples are drawn through large nozzles (0.25 to 1.0 in.), it has an advantage over the Brink cascade impactor where large particles are involved. The cut points of the three cyclones are 10, 3 and 1 micrometers. A detailed description of the SASS train is presented in Section 4.9.

4.5 COAL SAMPLING AND ANALYSIS PROCEDURE

Coal samples at Test Site E were taken during each test from the unit's two coal scales. The samples were processed and analyzed for both size consistency and chemical composition. The use of the coal scale as a sampling station has two advantages. It is close enough to the furnace that the coal sampled simultaneously with testing is representative of the coal fired during the testing. Also, because of the construction of the coal scale, it is possible to collect a complete cut of coal off the scales' apron feeder thus insuring a representative size consistency.

In order to collect representative coal samples, a sampling device having the same width as the apron feeder belt was moved directly under the belt's discharge end to catch all of the coal over a short increment of time (approximately five seconds).

The sampling procedure is as follows. At the start of testing, one increment of sample is collected from each feeder. This is repeated twice more during the test (three to five hours duration) so that a six increment sample is obtained. The sample is then riffled using a Gilson Model SP-2 Porta Splitter until two representative twenty pound samples are obtained.

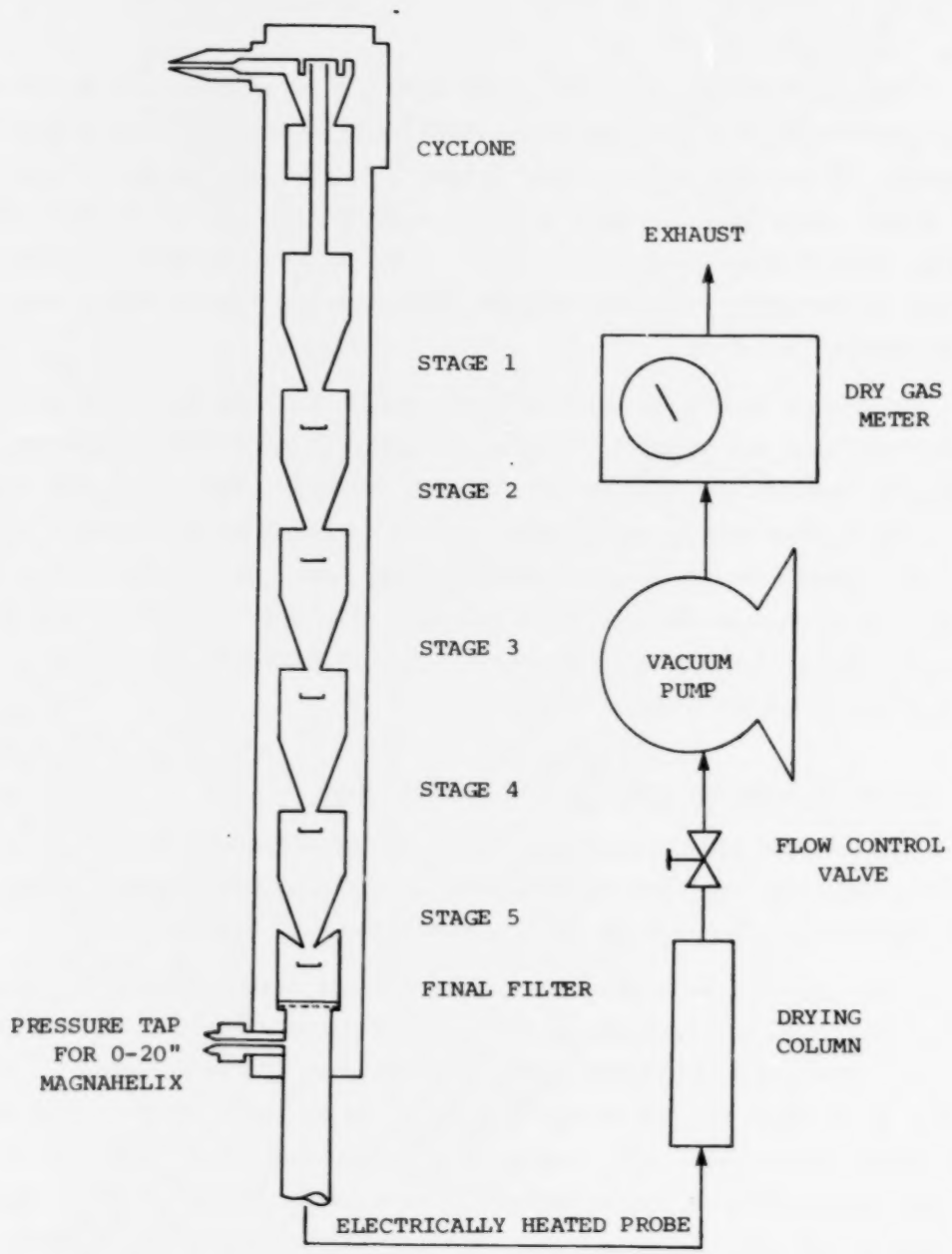


Figure 4-5. Brink Cascade Impactor Sampling Train Schematic

The sample to be used for sieve analysis is weighed, air dried overnight, and re-weighed. Drying of the coal is necessary for good separation of fines. If the coal is wet, fines cling to the larger pieces of coal and to each other. Once dry, the coal is sized using a six tray Gilson Model PS-3 Porta Screen. Screen sizes used are 1", 1/2", 1/4", #8 and #16 mesh. Screen area per tray is 14"x14". The coal in each tray is weighed on a triple beam balance to the nearest 0.1 gram.

The coal sample for chemical analysis is reduced to 2-3 pounds by further riffling and sealed in a plastic bag. All coal samples are sent to Commercial Testing and Engineering Company, South Holland, Illinois. Each sample associated with a particulate loading or particle sizing test is given a proximate analysis. In addition, composite samples consisting of one increment of coal for each test for each coal type receive ultimate analysis, ash fusion temperature, mineral analysis, Hardgrove grindability and free swelling index measurements.

4.6 ASH COLLECTION AND ANALYSIS FOR COMBUSTIBLES

The combustible content of flyash is determined in the field by KVB in accordance with ASTM D3173, "Moisture in the Analysis Sample of Coal and Coke" and ASTM D3174, "Ash in the Analysis Sample of Coal and Coke."

The flyash sample is collected by the EPA Method 5 particulate sample train while sampling for particulates. The cyclone catch is placed in a desiccated and tare-weighed ceramic crucible. The crucible with sample is heated in an oven at 230°F to remove its moisture. It is then desiccated to room temperature and weighed. The crucible with sample is then placed in an electric muffle furnace maintained at a temperature of 1400°F until ignition is complete and the sample has reached a constant weight. It is cooled in a desiccator over desiccant and weighed. Combustible content is calculated as the percent weight loss of the sample based on its post 230°F weight.

At Test Site E the bottom ash samples were collected in several increments from the discharge end of the grate during testing. These samples were mixed, quartered, and sent to Commercial Testing and Engineering Company for combustible determination. Multiclone ash samples and economizer ash

samples were taken from ports near the base of their hoppers. These samples, approximately two quarts in size, were sent to Commercial Testing and Engineering Company for combustible determination.

4.7 BOILER EFFICIENCY EVALUATION

Boiler efficiency is calculated using the ASME Test Form for Abbreviated Efficiency Test, Revised, September, 1965. The general approach to efficiency evaluation is based on the assessment of combustion losses. These losses can be grouped into three major categories: stack gas losses, combustible losses, and radiation losses. The first two groups of losses are measured directly. The third is estimated from the ABMA Standard Radiation Loss Chart.

Unlike the ASME test in which combustible losses are lumped into one category, combustible losses are calculated and reported separately for combustibles in the bottom ash, combustibles in the mechanically collected ash which is not reinjected, and combustibles in the flyash leaving the mechanical collector.

4.8 TRACE SPECIES MEASUREMENT

The EPA (IERL-RTP) has developed the Source Assessment Sampling System (SASS) train for the collection of particulate and volatile matter in addition to gaseous samples (Figure 4-6). The "catch" from the SASS train is analyzed for polynuclear aromatic hydrocarbons (PAH) and inorganic trace elements.

In this system, a stainless steel heated probe is connected to an oven module containing three cyclones and a filter. Size fractionation is accomplished in the series cyclone portion of the SASS train, which incorporates the cyclones in series to provide large quantities of particulate matter which are classified by size into three ranges:

A) >10 μm B) 3 μm to 10 μm C) 1 μm to 3 μm

With a filter, a fourth cut (>1 μm) is obtained. Volatile organic material is collected in an XAD-2 sorbent trap. The XAD-2 trap is an integral part of the gas treatment system which follows the oven containing the cyclone

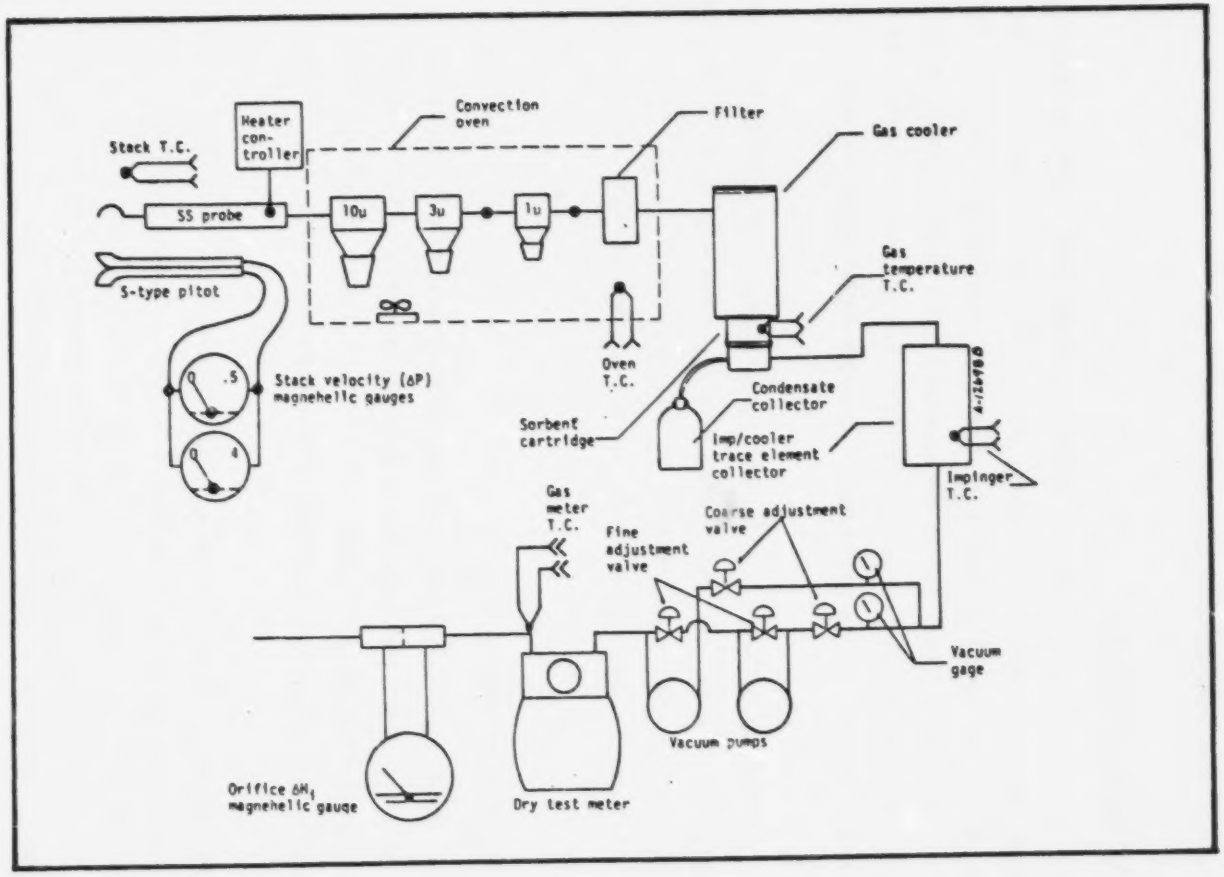


Figure 4-6. Source Assessment Sampling System (SASS) Flow Diagram

system. The gas treatment system is composed of four primary components: the gas conditioner, the XAD-2 organic sorbent trap, the aqueous condensate collector, and a temperature controller. The XAD-2 sorbent is a porous polymer resin with the capability of absorbing a broad range of organic species. Some trapping of volatile inorganic species is also anticipated as a result of simple impaction. Volatile inorganic elements are collected in a series of impingers. The pumping capacity is supplied by two 10 cfm high volume vacuum pumps, while required pressure, temperature, power and flow conditions are obtained from a main controller.

5.0 TEST RESULTS AND OBSERVATIONS

This section presents the results of the tests performed on Boiler E. Observations are made regarding the influence on efficiency and gaseous and particulate emissions as the control parameters were varied. Twenty tests were conducted in a defined test matrix to develop this data. Tables 5-19 through 5-22 are included at the end of this section for reference.

As was mentioned in the executive summary to this report, problems were encountered which prevented the entire test program from being completed. As a result, interpretation of some of the data is rendered very difficult. In general, however, the data obtained at Site E are useful and informative. These data are discussed in the following paragraphs.

5.1 OVERFIRE AIR

Boiler E had four rows of overfire air jets in the configuration shown in Figure 3-1. Several tests were run in which overfire air pressure to individual rows of air jets (and thus overfire air flow) was the independent variable. Emissions and boiler efficiency were measured as the overfire air pressures were varied in order to determine which overfire air pressure settings were optimum.

5.1.1 Overfire Air Flow Rate Measurements

Overfire air flow rates were determined for one pressure setting on each of the four rows of air jets. Overfire air flow rate was also determined at the overfire air fan outlet, thus allowing the flyash reinjection air flow, which is supplied by the same fan, to be determined by difference. These data are shown in Table 5-1.

Based on these measurements it is possible to determine the individual and total air flows into the furnace at any overfire air pressure setting. The relationship used to make this determination is derived from Bernaulli's

Preceding page blank

TABLE 5-1

OVERFIRE AIR FLOW RATES

TEST SITE E

Overfire Air Header	Static Pressure "H_2O	Measured Air Flow lbs/hr	Percentage of Total Overfire Air
Front Upper	24.0	13,200	31%
Front Lower	29.5	300	1%
Rear Upper	8.5	13,300	31%
Rear Lower	23.0	16,000	37%
	Total	42,800	100%

equation for fluid flow through an orifice. It has been verified by KVB on previous tests. One form of Bernaulli's equation is:

$$\frac{\Delta P}{\rho} = \frac{\Delta v^2}{2g}$$

The velocity (v) is proportional to the square root of the pressure drop (ΔP). At $\Delta P = 0$, $v = 0$. Therefore, a line drawn through the square root of each static pressure listed in Table 5-1 and through the (0,0) point will define the airflow or velocity as a function of $\sqrt{\Delta P}$ (Figure 5-1).

5.1.2 Particulate Loading vs Overfire Air

Four tests were run on Kentucky coal to determine the effect of adjustments to the overfire air system on particulate emissions. The results are shown in Figure 5-2 and in Table 5-2.

The results show that reducing the overfire air pressure to the rear upper and lower rows of air jets had no effect on particulate loading. This conclusion is based on the results of test 8 which averaged 27"H_2O pressure on the rear jets, and test 11 which averaged 3"H_2O pressure on the rear jets. The boiler outlet particulate loadings for tests 8 and 11 were 4.49 and 4.32 lbs/10^6 Btu, respectively, which is not a significant difference. Both tests were run under similar conditions of boiler loading and excess air.

Test 6 had the lowest particulate loading of any test run at this site and it is not understood why this was the case. It is suspected that high excess air played a part. The overfire air settings during test 6 were the normal day-to-day operating settings for this unit.

When the air pressure to the lower front and lower rear rows of overfire air jets was reduced, as it was during test 7, the boiler outlet particulate loading increased to 5.23 lbs/10^6 Btu. This increase is significant when compared to test 8 (4.49 lbs/10^6 Btu), but it must be noted that the variable excess air was not held constant. Therefore, it is entirely possible that the increase in particulate loading was due to reduced excess air and not the change in overfire air conditions. Figure 5-2 shows that the increased particulate loading of test 7 resulted entirely from its increased combustible content when compared to test 8.

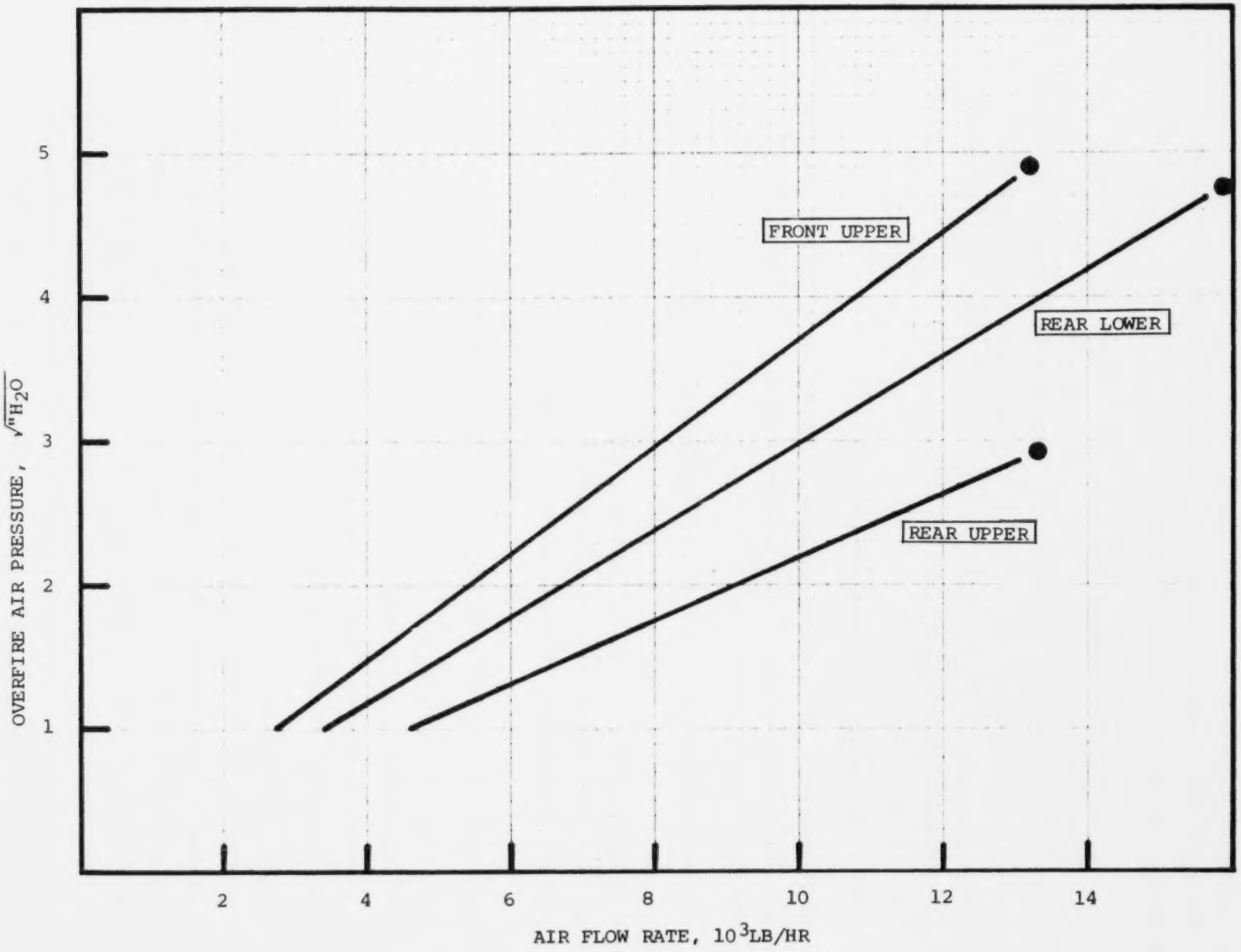


Figure 5-1. Pressure-Flow Relationship, Overfire Air System, Test Site E

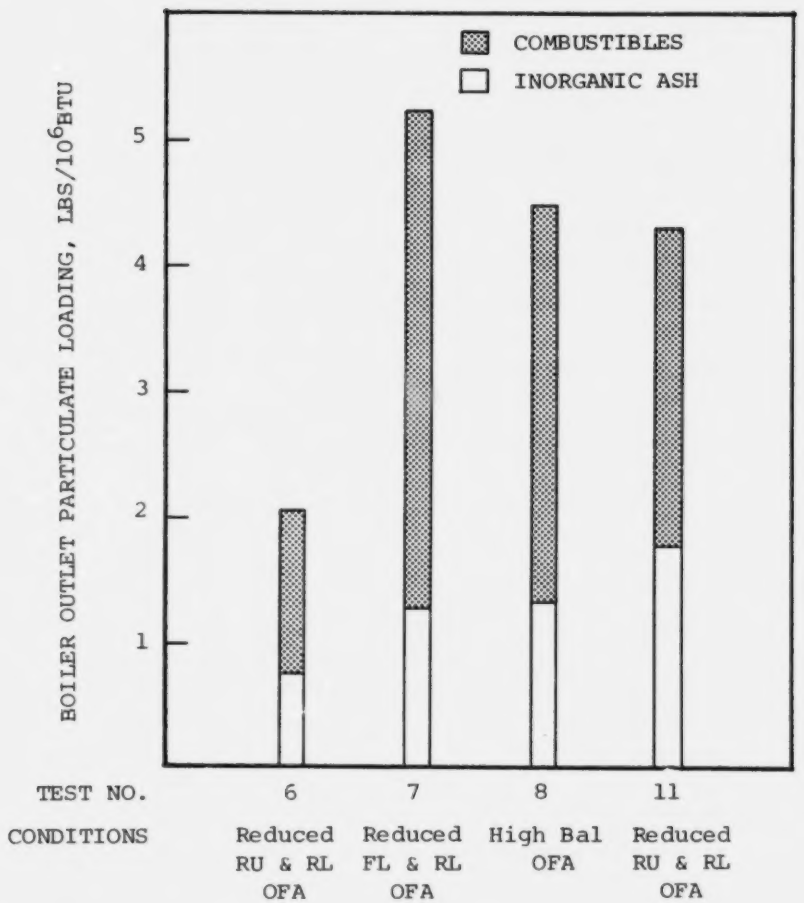


Figure 5-2. Particulate Loading Breakdown for Kentucky Coal as a Function of Overfire Air Conditions.

TABLE 5-2

EFFECT OF OVERFIRE AIR ON EMISSIONS AND EFFICIENCY
KENTUCKY COAL - TEST SITE E

TEST NO.	6	7	8	11
DESCRIPTION	Reduced RU & RL OFA (Baseline)	Reduced FL & RL OFA	High Bal OFA	Reduced RU & RL OFA
OVERFIRE AIR CONDITIONS				
Front Upper, "H_2O	28	28	28	28
Front Lower, "H_2O	31	19	28	28
Rear Upper, "H_2O	3	28	28	3
Rear Lower, "H_2O	19	19	26	3
FIRING CONDITIONS				
Load, % of Capacity *	65	67	61	62
Grate Heat Release, 10^3Btu/hr-ft^2	454	504	458	454
Coal Sizing, % Passing 1/4"	34	34	34	31
Excess Air, %	70	29	43	40
BOILER OUTLET EMISSIONS				
Particulate Loading, lb/10^6Btu	2.060	5.230	4.493	4.316
Combustible Loading, lb/10^6Btu	1.283	3.938	3.172	2.529
Inorganic Ash Loading, lb/10^6Btu	0.777	1.292	1.321	1.787
Combustibles in Flyash, %	62.3	75.3	70.6	58.6
O_2, % (dry)	9.0	5.2	6.8	6.5
CO, ppm (dry) @ 3% O_2	62	147	--	--
NO, lb/10^6Btu	0.614	0.494	0.493	0.480
MULTICLONE OUTLET EMISSIONS				
Particulate Loading, lb/10^6Btu	0.335	1.824	0.190	1.558
Combustible Loading, lb/10^6Btu	0.205	1.226	--	0.966
Inorganic Ash Loading, lb/10^6Btu	0.130	0.598	--	0.592
Combustible in Flyash, %	61.2	67.2	--	62.0
Multiclone Collection Efficiency, %	83.7	65.1	95.8	63.9
Stack Opacity, %	17	45	38	46
HEAT LOSSES, %				
Dry Gas Loss	7.60	6.55	7.32	6.85
Moisture in Fuel	0.63	0.43	0.40	0.48
H_2O from Combustion of H_2	3.88	3.78	3.89	3.85
Combustibles in Boiler Outlet Flyash	5.89	5.64	4.52	3.60
Combustibles in Bottom Ash	1.17	0.76	0.31	1.55
Radiation Loss	0.71	0.68	0.75	0.73
Unmeasured Losses	1.50	1.50	1.50	1.50
Total Losses	21.38	19.34	18.69	18.56
Boiler Efficiency	78.62	80.66	81.31	81.44

*Design capacity of boiler is 180,000 lb steam/hr. Maximum obtainable load was 60-70% of design capacity due to retrofit combustion air system.

5.1.3 Nitric Oxide vs Overfire Air

The nitric oxide data obtained at Test Site E indicates that overfire air changes had little or no effect on nitric oxide emissions. The nitric oxide data are presented in Table 5-3.

An effort was made to sort out the effects of differing oxygen levels on nitric oxide emissions so that overfire air setting would be the only variable. This was accomplished by first fitting a line to the NO vs O_2 data in the load range of interest. Linear regression by least squares was used to do this. The slope of this line was then used to correct the nitric oxide data to a constant 9% O_2.

Having corrected for the effects of oxygen, the data compared as follows: Tests 10b and 10d were carried out under identical conditions, except for the biasing of the overfire air pressure to the lower and upper rear rows of air jets. In these two tests NO changed from 0.582 to 0.592 lbs/10^6 Btu corrected, an insignificant change.

Tests 8 and 11 were carried out under identical conditions, except that test 8 had high pressure to both rear rows of air jets and test 11 had low pressure to the same rows. In these two tests NO changed from 0.552 to 0.548 lbs/10^6 Btu corrected, again an insignificant change.

5.1.4 Boiler Efficiency vs Overfire Air

Boiler efficiency data for the overfire air tests are shown in Table 5-2. Because overfire air changes would be expected to effect primarily the combustibles-in-flyash heat loss, these data are presented in Table 5-4. The lowest heat loss due to combustibles in the flyash occurred during test 11, which had high overfire air pressures on the front jets and low pressures on the rear jets. There is no evidence that overfire settings were responsible for the low combustible heat loss.

TABLE 5-3

NITRIC OXIDE EMISSIONS vs OVERFIRE AIR
TEST SITE E

Test No.	Coal	% Design Capacity	O_2 %	Overfire Air Pressure, "H_2O FU	FL	RU	RL	Nitric Oxide, lb/10^6 Btu Measured	Corrected*
6	Kentucky	65	9.0	28	31	3	19	.614	.614
7	Kentucky	67	5.2	28	19	28	19	.494	.597
8	Kentucky	61	6.8	28	28	28	26	.493	.552
10b	Kentucky	61	7.6	31	ND	3	29	.544	.582
10d	Kentucky	61	8.2	31	ND	31	9	.570	.592
11	Kentucky	62	6.5	28	28	3	3	.480	.548

* Corrected to 9% O_2 by applying the established O_2-NO relationship:
1% O_2 increase = 0.027 lbs/10^6 Btu Nitric Oxide increase.

FU -- front upper
FL -- front lower
RU -- rear upper
RL -- rear lower
ND -- no data

TABLE 5-4

COMBUSTIBLES IN FLYASH vs OVERFIRE AIR
TEST SITE E

Test No.	Coal	% Design Capacity	O_2 %	Overfire Air Pressure, "H_2O FU	FL	RU	RL	% Comb. in Flyash	% Comb. Heat Loss
6	Kentucky	65	9.0	28	31	3	19	62.3	5.89
7	Kentucky	67	5.2	28	19	28	19	75.3	5.64
8	Kentucky	61	6.8	28	28	28	26	70.6	4.52
11	Kentucky	62	6.5	28	28	3	3	58.6	3.60

FU -- front upper
FL -- front lower
RU -- rear upper
RL -- rear lower

5.2 EXCESS OXYGEN AND GRATE HEAT RELEASE

The boiler at Test Site E was tested for emissions and boiler efficiency under a variety of operating conditions. This section presents the results of these emissions and efficiency tests as a function of load, expressed as grate heat release, and excess air, expressed as percent oxygen in the flue gas. The data are also differentiated by coal type in many of the plots.

Before examining the test data it is important to understand the special nature of the combustion air on this boiler, and corrections that have been made to the steam flow readings.

The boiler at Test Site E was recently retrofitted with a new combustion air system. This system, which uses paint oven exhaust gasses for combustion air, has reduced the steam capacity of the boiler by about 30% or 55,000 lbs stm/hr. The majority of tests at this test site were run at the maximum obtainable load, but were limited by fan capacity to the range 110-125 thousand pounds of steam per hour.

It is also worth noting that the paint oven exhaust gasses contained varying amounts of oxygen in the range 14.5 - 20.5% O_2. These combustion air oxygen levels are included in the Emission Data Summary, Table 2-1.

During three tests -- tests 3, 9, 20 -- the boiler was operated on ambient air. These tests are identified in the plots by the use of solid rather than open symbols. The same load restriction was experienced when using ambient air as was experienced when using paint oven exhaust gasses. The same retrofit FD fan was used in both cases.

The steam flow and percent boiler loading data reported herein have been corrected for a calibration error in the steam flow integrator. The steam flow integrator was found to be 20,000 lbs/hr low by a Hays repairman subsequent to the test program at site E. Consequently, all measured steam flows have been corrected upwards by 20% to compensate for the error.

5.2.1 Excess Oxygen Operating Levels

Figure 5-3 depicts the various conditions of grate heat release and

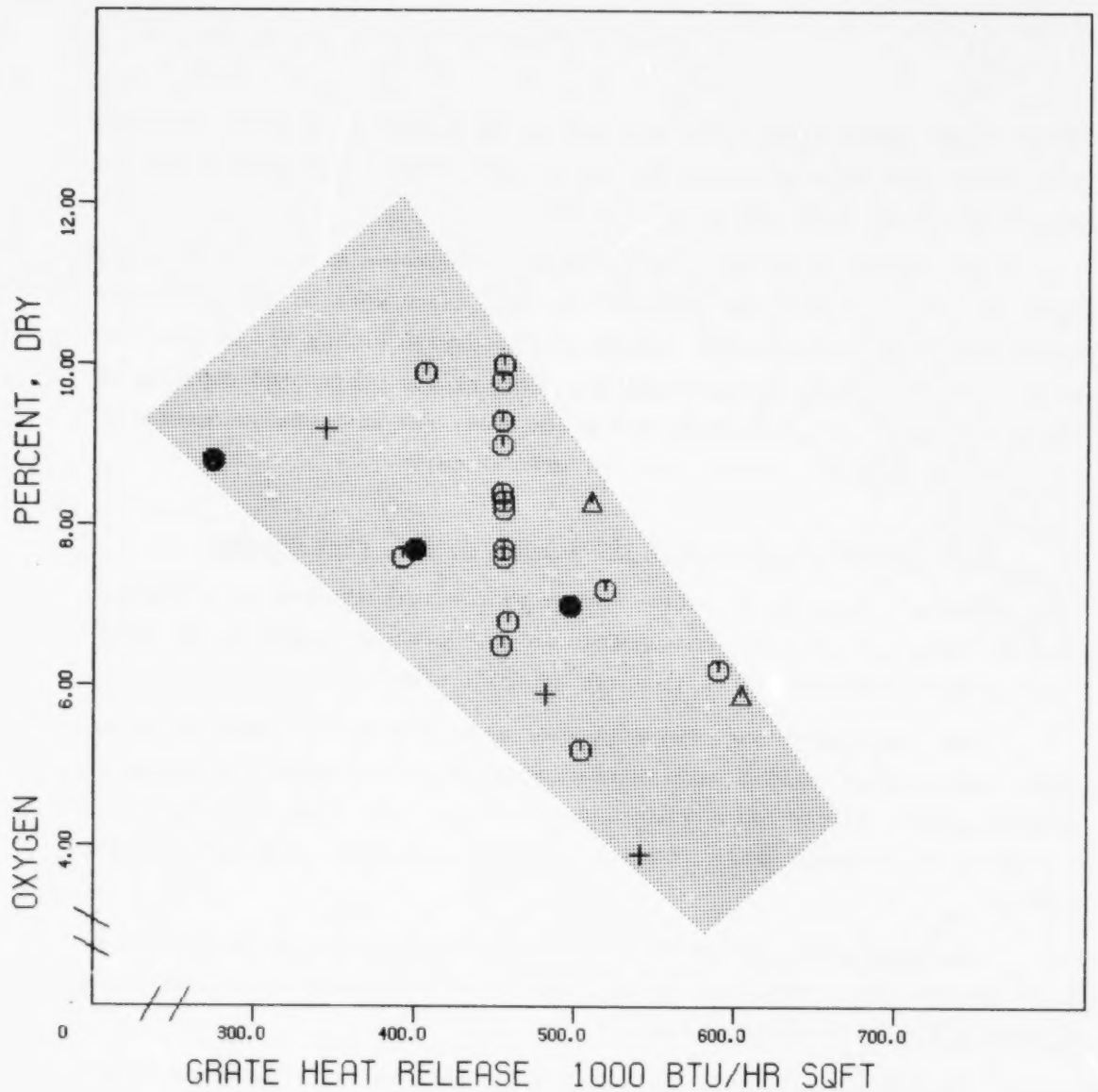


FIG. 5-3
OXYGEN VS. GRATE HEAT RELEASE
TEST SITE E

excess oxygen under which tests were run on the boiler at site E. Different symbols are used to distinguish the three coals fired. The three solid symbols are those tests run on ambient air.

The oxygen operating level is shown to decrease with increasing load, expressed here as grate heat release. If this trend were to continue, the boiler would easily be able to operate at its design excess air of 30%, or about 5.3% O_2, at full design capacity. Even at its restricted capacity of between 500 and 600 x 10^3 Btu/hr-ft^2 grate area, the unit was successfully operated near this excess air level on several tests.

5.2.2 Particulate Loading vs Oxygen and Grate Heat Release

Figure 5-4 profiles boiler outlet particulate loading as a function of grate heat release. The data points in this plot are keyed to the coal fired with the ambient air tests shown as solid symbols.

With two exceptions, the data show a defined upward trend in boiler outlet particulate loading with increasing grate heat release. No explanation could be found for the two anomolous data points. The upper one, test 5, was a baseline or as-found test. The lower one, test 6, was a low overfire air test.

The average boiler outlet particulate loading at high load was 5.51 ± .66 lbs/10^6 Btu. High load on this unit is defined as a grate heat release of 500x10^3 Btu/hr - ft^2 or greater.

The average ash carryover was 20% in these tests. Table 5-5 shows the average ash content of the three coals and the percentage of this ash which was carried over with the flyash. Note that only the inorganic ash fraction of the flyash is considered in making this determination. Average ash contents of the three coals were nearly identical.

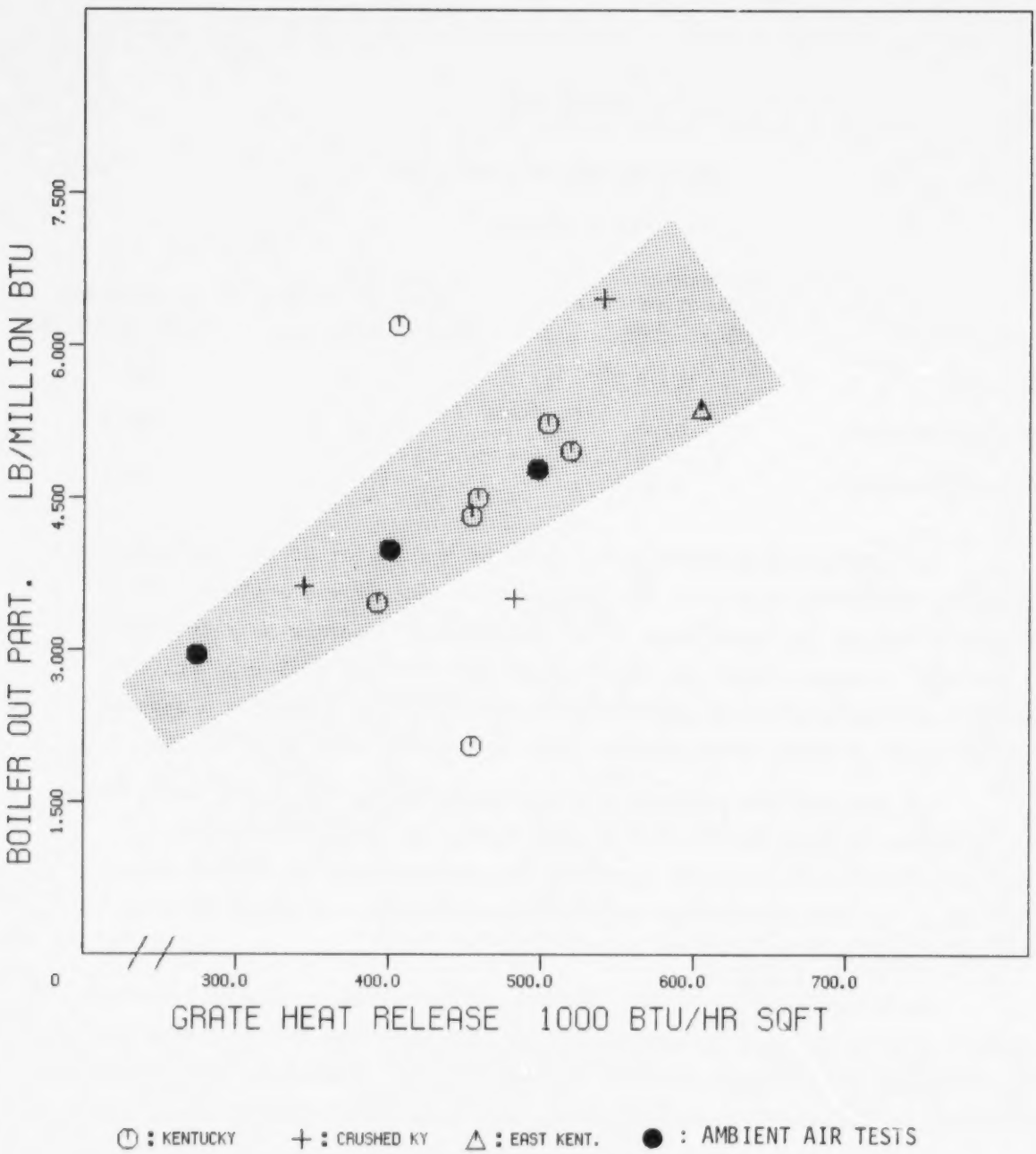


FIG. 5-4
BOILER OUT PART. VS. GRATE HEAT RELEASE
TEST SITE E

TABLE 5-5

ASH CARRYOVER VS COAL TYPE

TEST SITE E

Coal	Average Ash Content of Coal, lbs/10^6 Btu	Average Ash Content of Flyash, lbs/10^6 Btu	Average Ash Carryover, %
Kentucky	6.78	1.34	19.7
Crushed Kentucky	6.80	1.45	21.3
Eastern Kentucky	6.39	2.14	33.4

Particulate measurements were made at the outlet of the multiclone dust collector simultaneously with the measurements made at the boiler outlet. Figure 5-5 plots the multiclone outlet particulate loadings as a function of grate heat release. Again the data points are keyed to coal type and the ambient air tests are indicated by solid symbols. The data show a general upward trend in particulate loading with increasing grate heat release.

The particulate loadings are very scattered at the multiclone outlet. It is suspected that the multiclone dust collector hopper was filled to capacity during several tests resulting in reintrainment of the ash and a lowered collection efficiency. Multiclone collection efficiency will be discussed in section 5.5.

At both the boiler outlet and the multiclone dust collector outlet, the ambient air particulate test data were no different than the data from tests run on paint oven exhaust gasses. Therefore, it is concluded that this unique retrofit to the boiler at site E has no impact on particulate emission levels.

5.2.3 Stack Opacity vs Oxygen and Grate Heat Release

Stack opacity was measured during most tests by a transmissometer mounted between the multiclone outlet and the inlet to the induced draft fan.

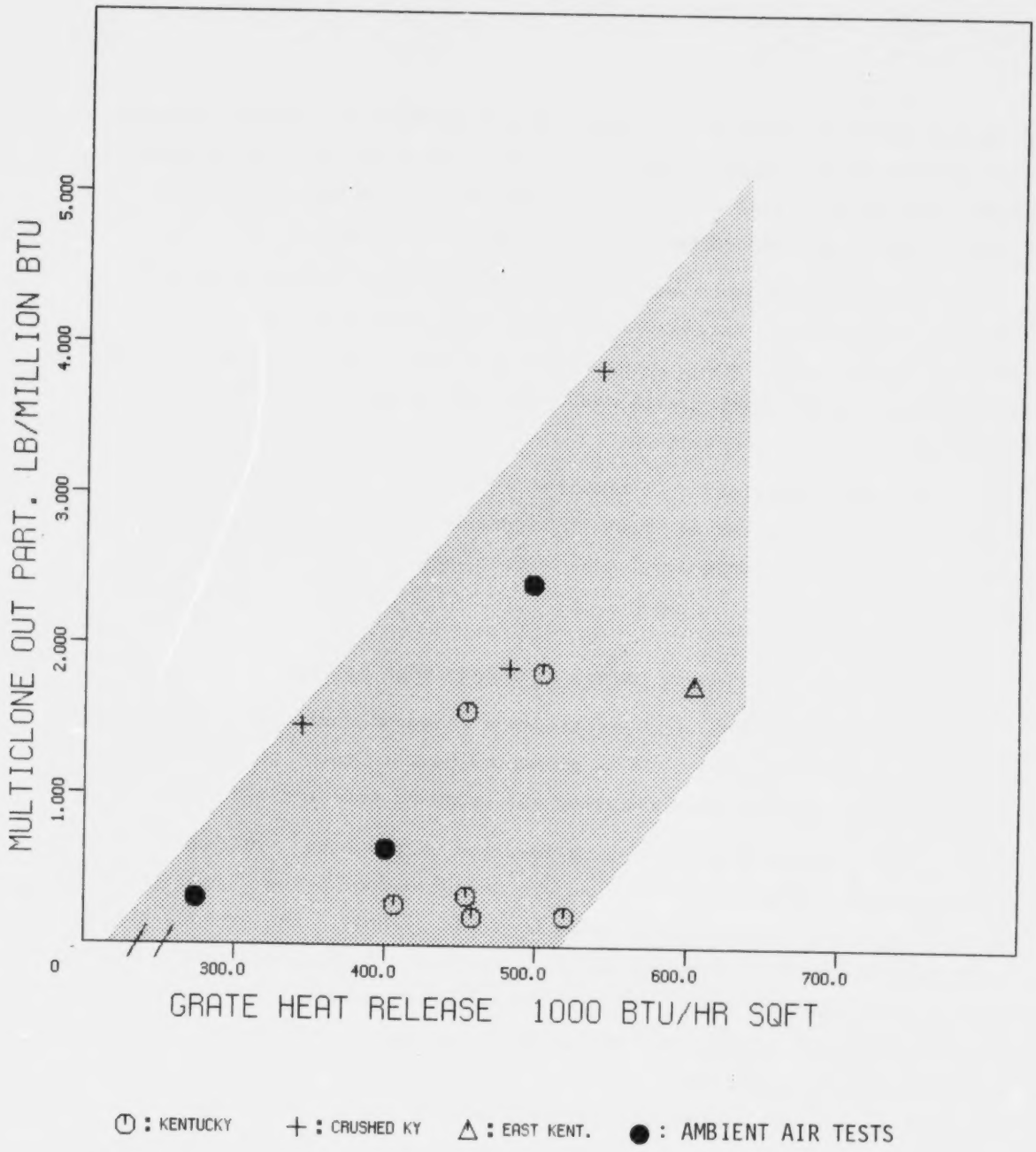


FIG. 5-5
MULTICLONE OUT PART. VS. GRATE HEAT RELEASE
TEST SITE E

It became apparent during the course of testing that the opacity readings were increasing with time as the light source and light receiver glasses became covered with dust or soot. Thus beginning with test no. 5, the sight glasses were cleaned prior to each opacity reading.

Figure 5-6 presents the opacity readings taken at site E as a function of grate heat release. This plot shows that there is no obvious trend in opacity data versus load. This plot also shows that there may be some correlation of opacity with coal type, but there is insufficient data to substantiate this speculation.

A better correlation is obtained by plotting opacity against multiclone outlet particulates as shown in Figure 5-7. This plot again indicates that changes in coal composition and combustion air flow were not factors in opacity level.

5.2.4 Nitric Oxide vs Oxygen and Grate Heat Release

Nitric oxide (NO) concentration was measured during each test in units of parts per million (ppm). It is presented here in units of $lbs/10^6$ Btu to be more easily compared with existing and proposed emission standards.

Nitric oxide is plotted as a function of grate heat release in Figure 5-8. The data points in this figure are keyed to coal being fired, while the three ambient air tests are indicated by solid symbols. The average nitric oxide concentration at high boiler loading (above $500X10^3$ $Btu/hr-Ft^2$) was 0.533 ± 0.047 $lbs/10^6$ Btu. Figure 5-8 does not isolate the variable oxygen, and therefore, the trend shown is for NO versus grate heat release under normal operating conditions. Ignoring the three ambient air tests, nitric oxide concentration is seen to be highest at low loads on this unit. The maximum measured NO was 0.65 $lbs/10^6$ Btu at a load of 48% design capacity. The ambient air tests produced nitric oxide concentrations which were generally lower than the tests utilizing paint oven exhaust gasses as combustion air. This was especially evident in the two lower load tests.

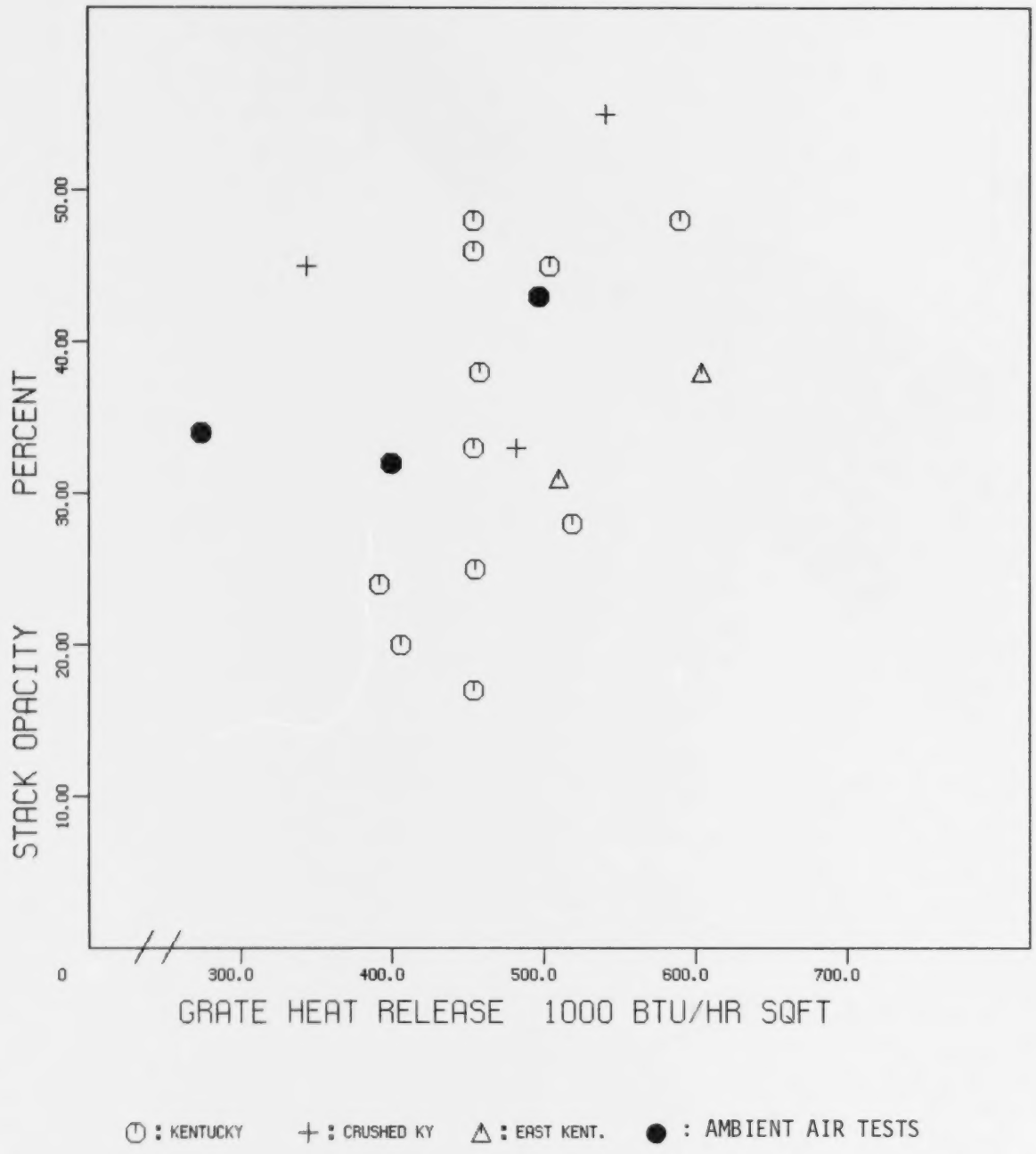


FIG. 5-6
STACK OPACITY VS. GRATE HEAT RELEASE
TEST SITE E

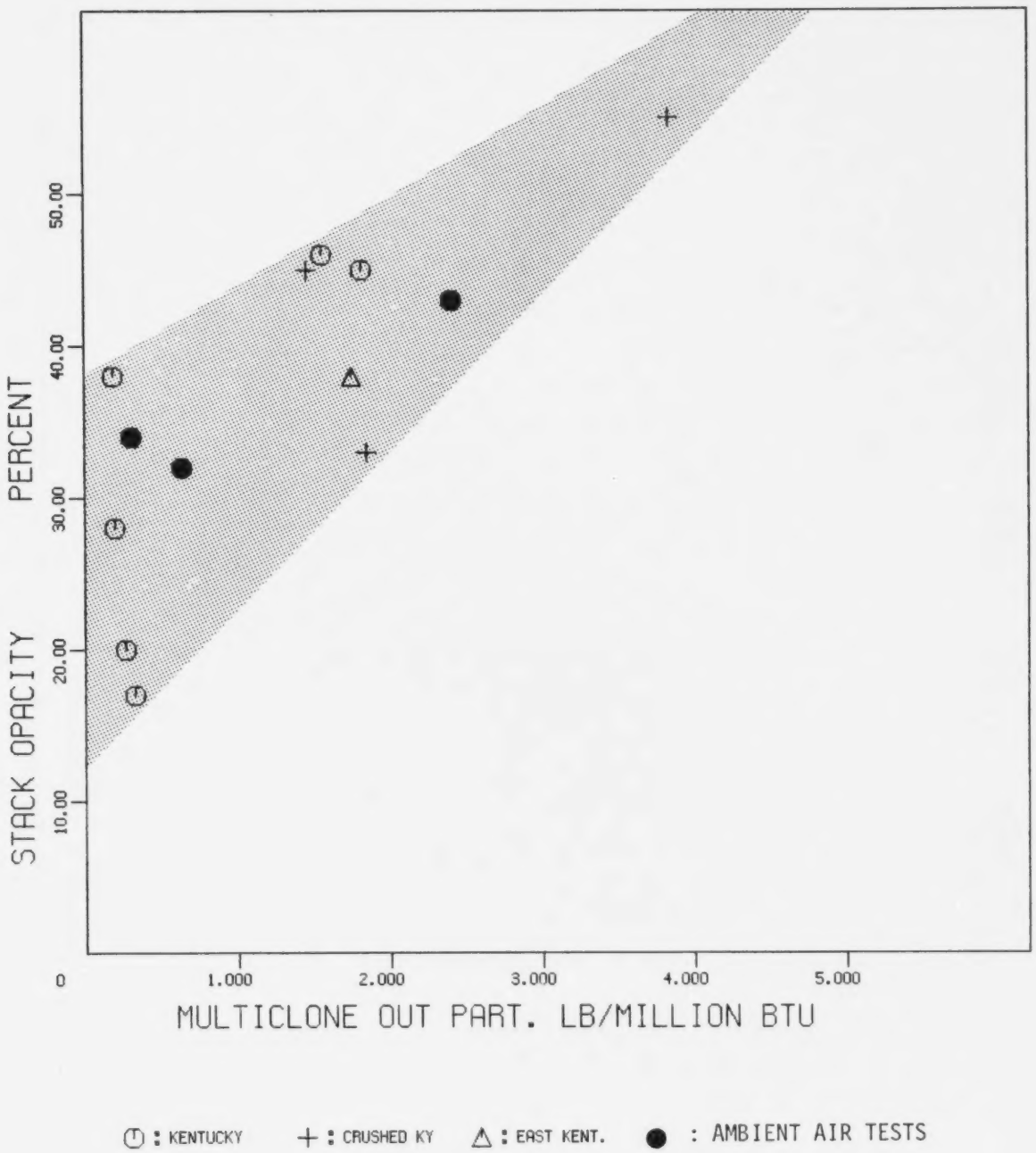


FIG. 5-7
STACK OPACITY VS. MULTICLONE OUT PART.
TEST SITE E

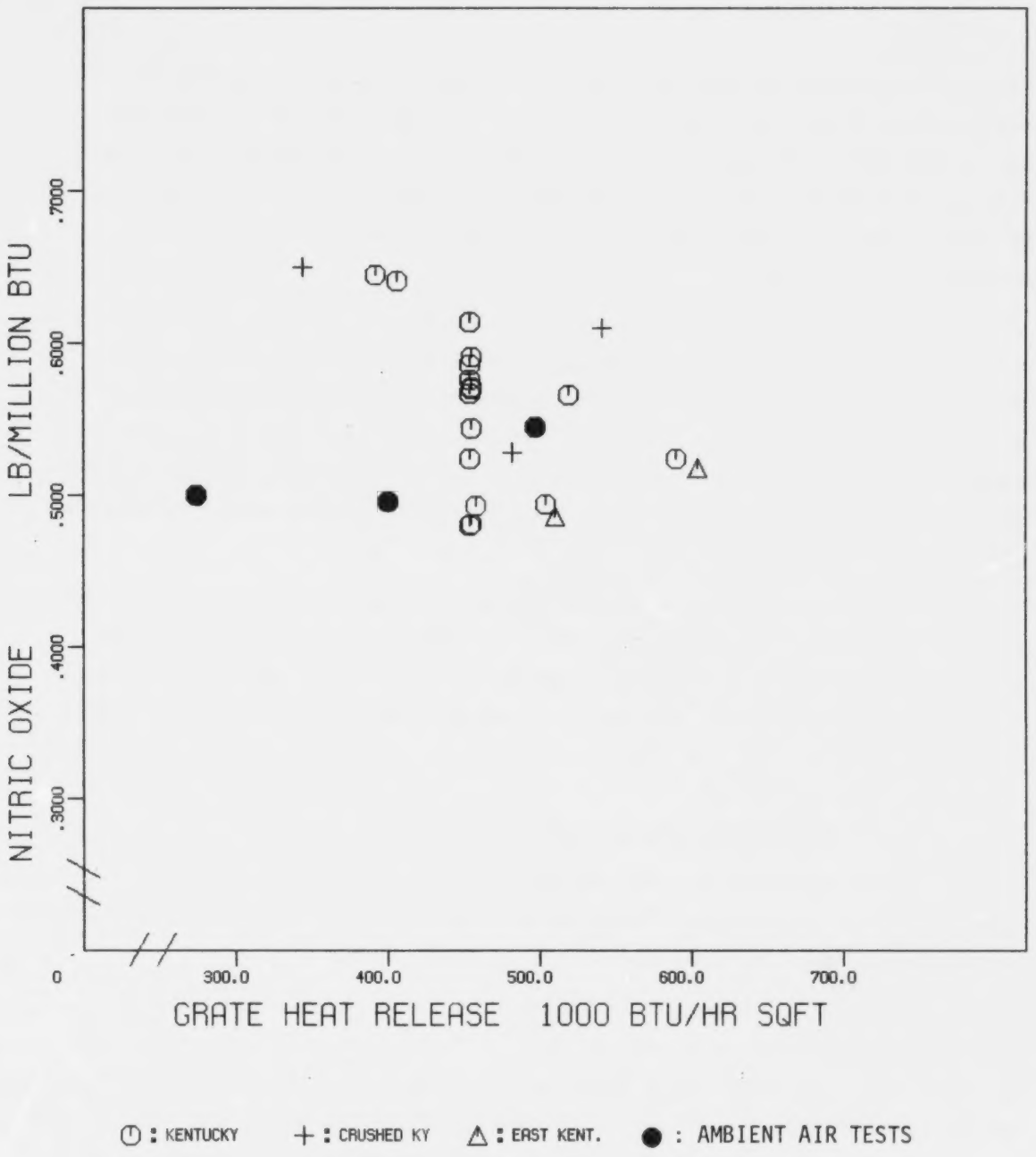


FIG. 5-8
NITRIC OXIDE VS. GRATE HEAT RELEASE
TEST SITE E

Nitric oxide concentration was found to increase sharply with oxygen at constant boiler load. There are a few data points which cannot be explained, but on the whole, the data gives a good NO vs O_2 profile for the boiler at Site E. All the NO data are plotted against oxygen in Figure 5-9, and the NO data in specific grate heat release ranges are plotted against O_2 in Figures 5-10, 5-11 and 5-12.

A nitric oxide trend line has been applied to the data in Figures 5-11 and 5-12 using linear regression analysis by method of least squares. The slope of these two trend lines indicates the following relationships. Nitric oxide increases by .027 lbs/10^6 Btu for each one percent increase in oxygen at 400-499x10^3 Btu/hr-ft^2 grate area. Nitric oxide increases by .037 lbs/10^6 Btu for each one percent increase in oxygen at 500-605x10^3 Btu/hr-ft^2 grate area.

Combining the trend lines for the two main grate heat release ranges produces the plot shown in Figure 5-13. The low load data, i.e., 300-399 GHR, was not included in this plot. Because of their extreme variance from the expected relationship, the two low load data points should be considered suspect.

5.2.5 Carbon Monoxide vs Oxygen and Grate Heat Release

Carbon monoxide (CO) was measured during the first seven tests at Site E. The CO analyzer was inoperative at the start of Test 8 and remained out of service for the remainder of the testing at this site.

The CO data are presented in units of parts-per-million (ppm) by volume on a dry basis, corrected to 3% O_2. Carbon monoxide is a by-product of incomplete combustion and a sensitive indicator of combustion problems, but if it is kept below 400 ppm it is considered insignificant for the purposes of this report. As a reference, 400 ppm CO is equivalent to 0.04% CO and represents a 0.20% heat loss in a coal fired boiler operating at 8% O_2. Figure 5-14 presents the carbon monoxide data gathered under a variety of firing conditions and plotted as a function of grate heat release.

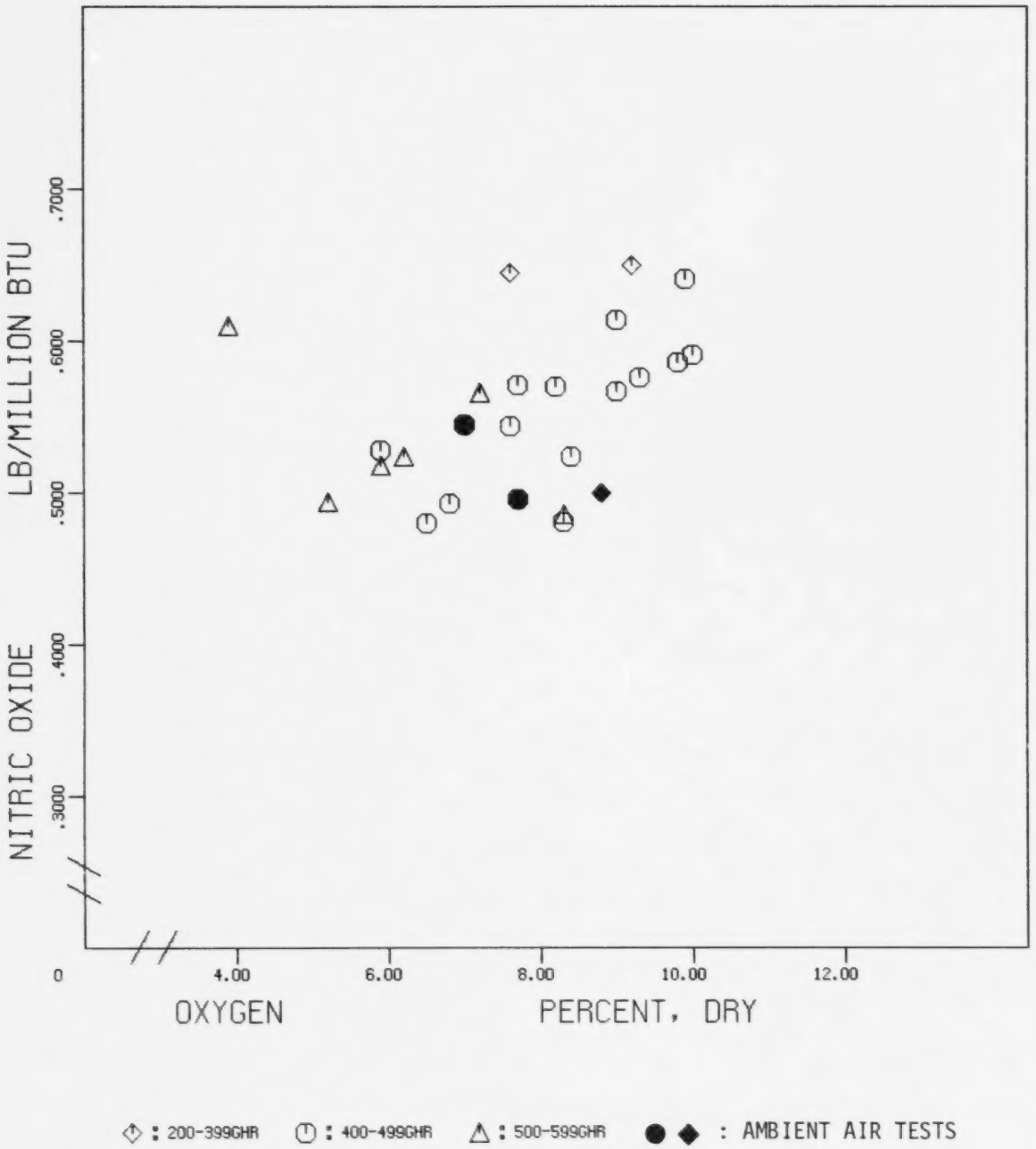


FIG. 5-9
NITRIC OXIDE VS. OXYGEN
TEST SITE E

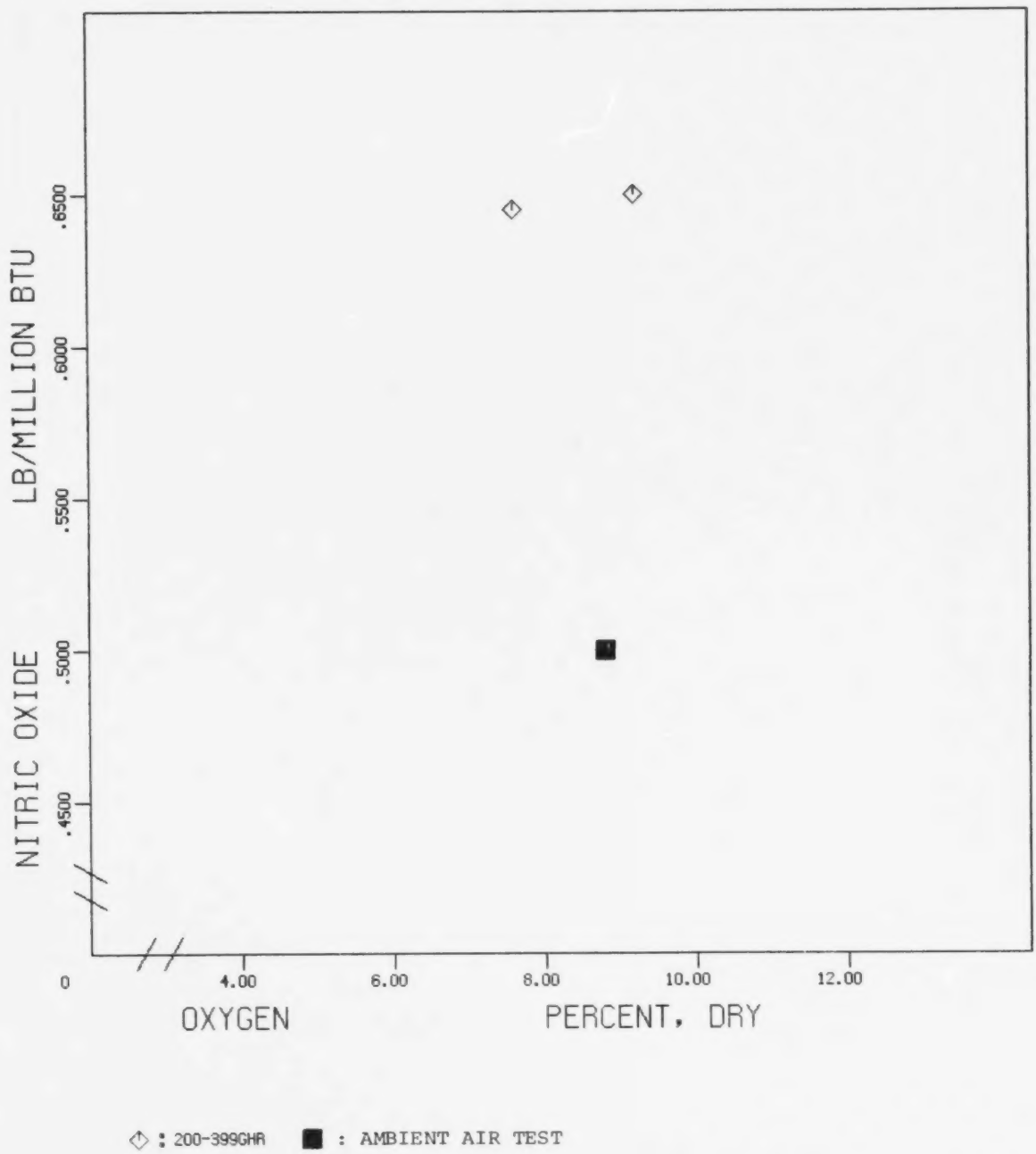
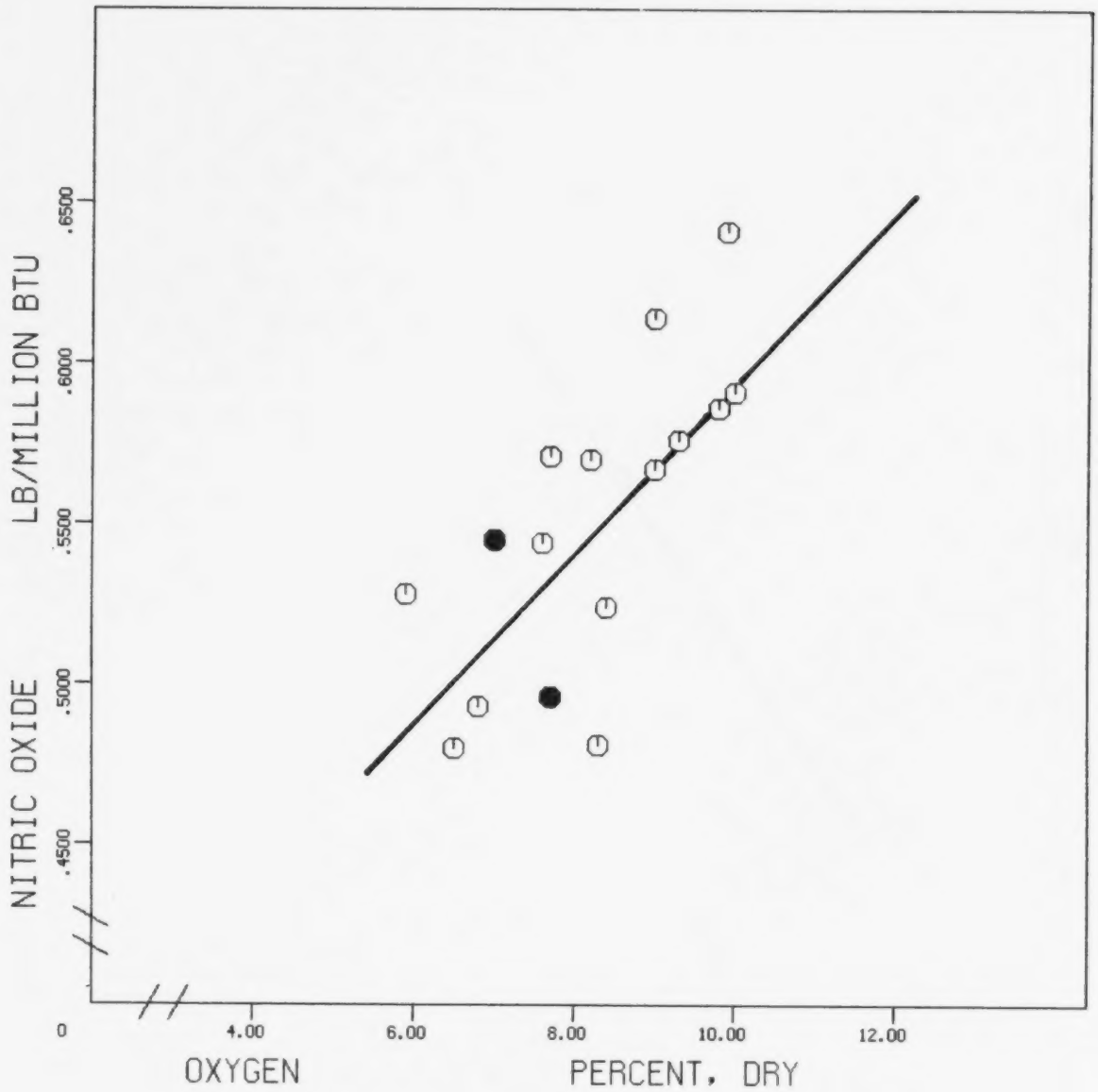


FIG. 5-10
NITRIC OXIDE VS. OXYGEN
TEST SITE E



⏲ : 400-499GHR ● : AMBIENT AIR TESTS

FIG. 5-11
NITRIC OXIDE VS. OXYGEN
TEST SITE E

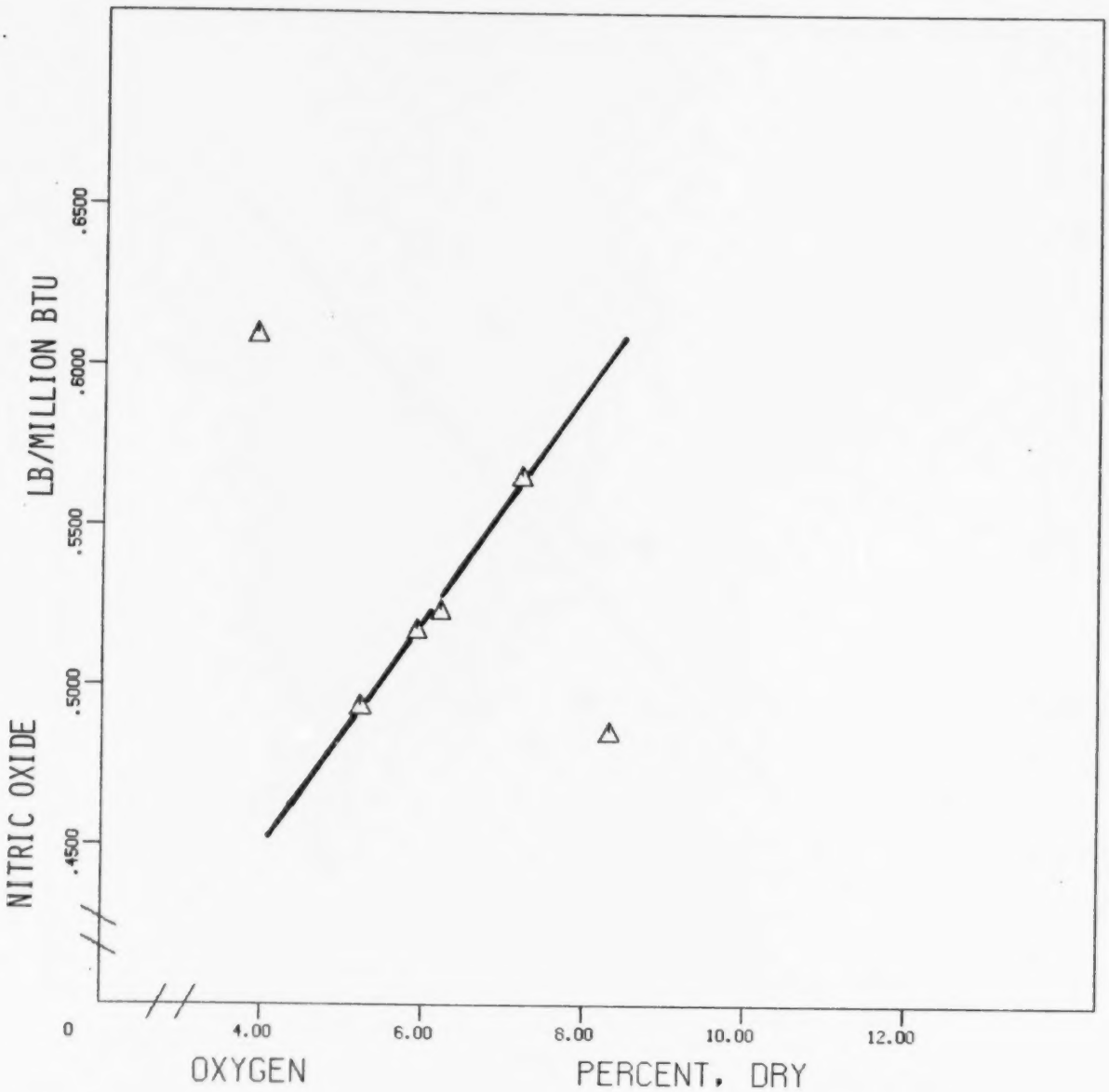


FIG. 5-12
NITRIC OXIDE VS. OXYGEN
TEST SITE E

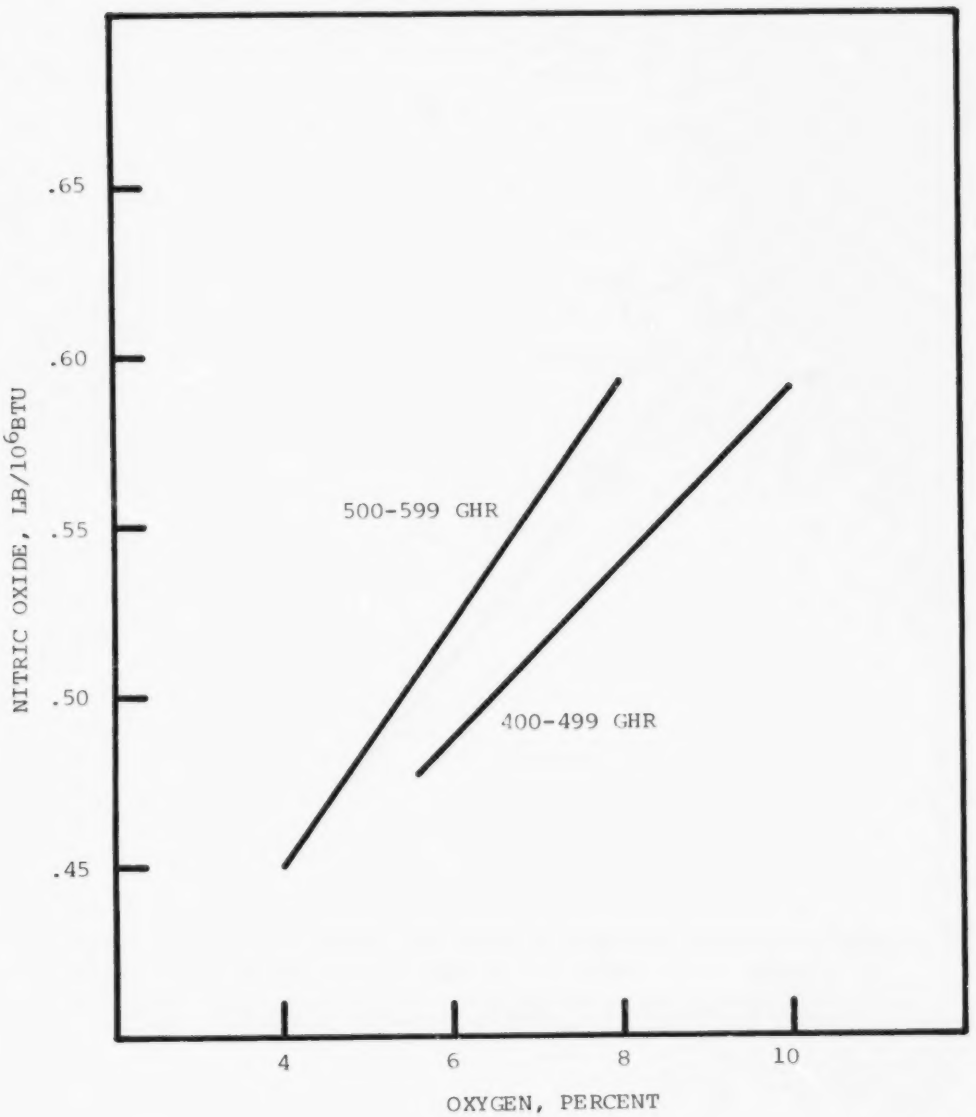
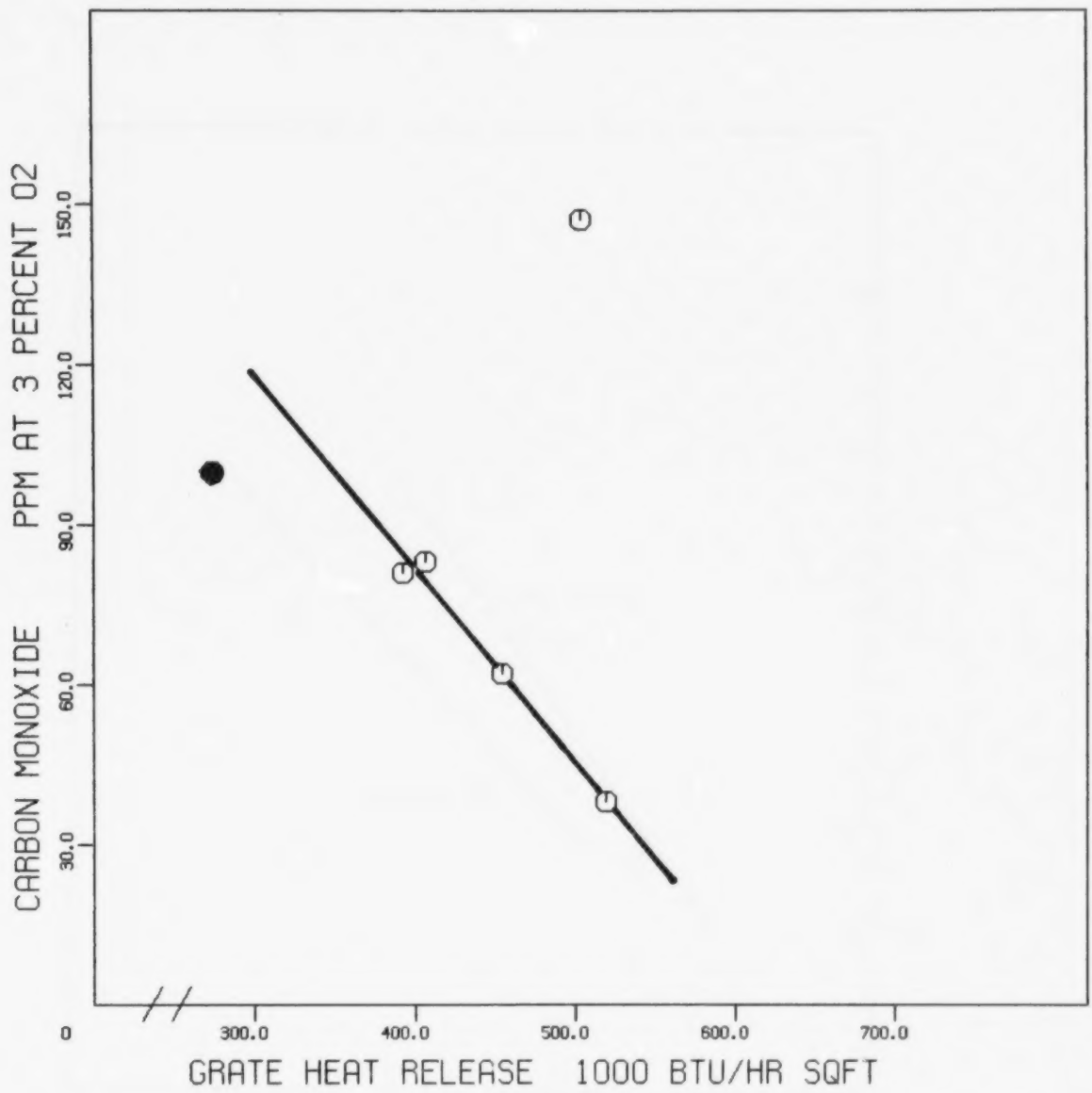


FIGURE 5-13. Trend in Nitric Oxide Emissions as a Function of Grate Heat Release (GHR) and Oxygen at Site E.



Ⓣ : KENTUCKY

● : AMBIENT AIR TESTS

FIG. 5-14
CARBON MONOXIDE VS. GRATE HEAT RELEASE
TEST SITE E

With one exception the trend shows decreasing CO with increasing grate heat release. The one exception was Test 7, a low O_2 test. All measured CO concentrations were low, and insignificant in terms of their contribution to incomplete combustion and heat loss.

Figure 5-15 presents the measured carbon monoxide data as a function of oxygen. There are only weak indications of a trend here. The highest CO concentration measured was also at the lowest oxygen level.

5.2.6 Combustibles vs Oxygen and Grate Heat Release

In this report the term "combustibles" refers only to the solid combustibles in the various ashes leaving the boiler. Combustibles are described here in terms of their percent by weight in the flyash at the boiler outlet and in the bottom ash collected from the ash pit.

Figure 5-16 shows the combustibles in the boiler outlet flyash as a function of grate heat release. The data points are keyed to coal, and the solid symbols refer to ambient air tests. Boiler outlet combustibles ranged from 50 to 84% on the spreader stoker, and averaged 66% overall. They accounted for an average 4.40 ± 0.89% heat loss. All three coals produced flyash combustible levels which were in the same general range. It is also evident that the ambient air tests produced flyash combustibles in the same range as the paint oven exhaust gas tests. The flyash combustible level showed an increasing trend with grate heat release.

Figure 5-17 shows the combustibles in the bottom ash as a function of grate heat release. The bottom ash combustibles ranged from 6 to 17% by weight and averaged 10% overall. They accounted for an average 0.87 ± 0.41% heat loss. Variations in coal and combustion air composition did not significantly affect bottom ash combustible levels.

5.2.7 Boiler Efficiency vs Oxygen and Grate Heat Release

Boiler efficiency was determined for each test that included a boiler outlet particulate loading measurement. The efficiency determinations were made by the ASTM heat loss method.

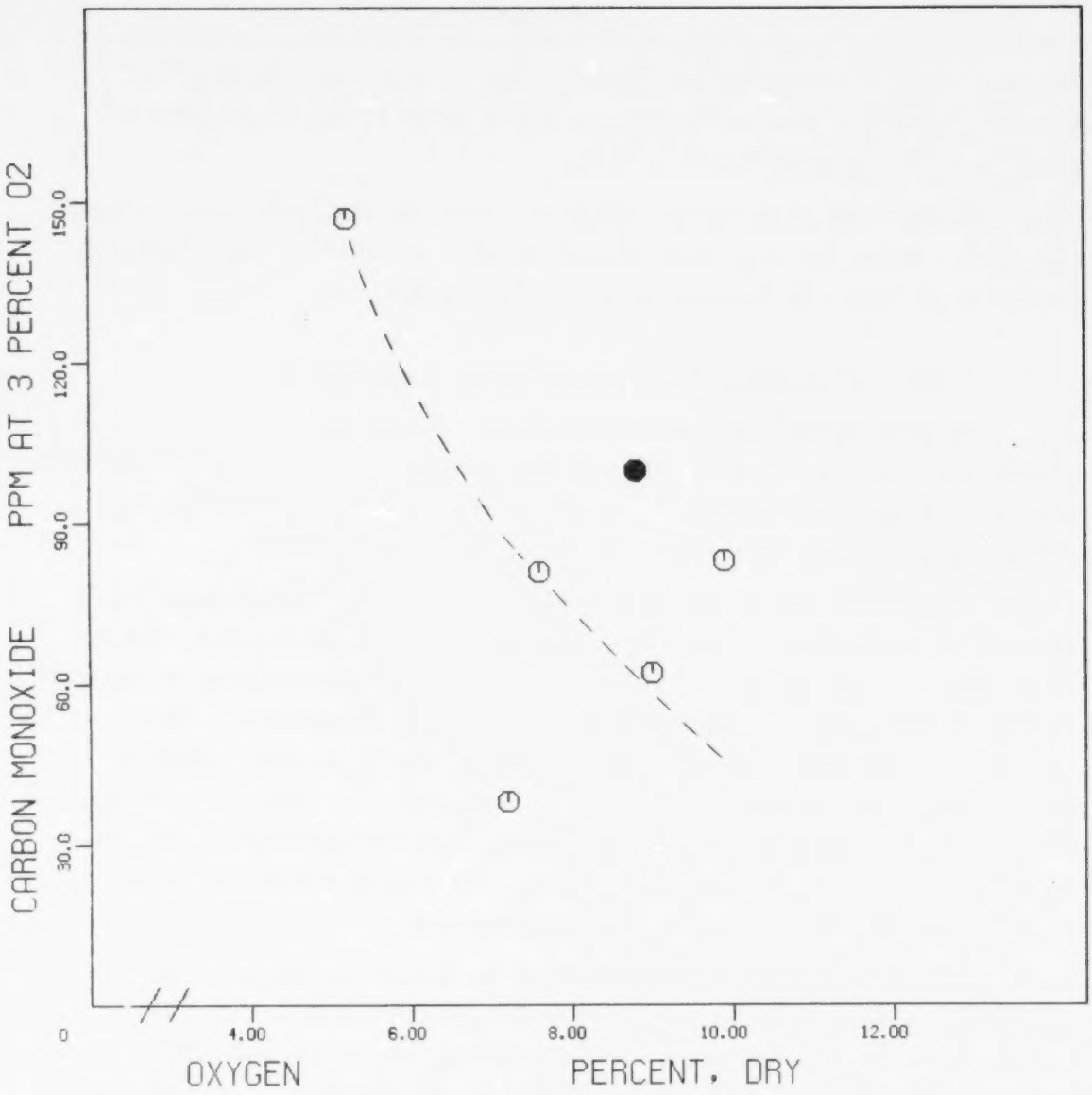


FIG. 5-15
CARBON MONOXIDE VS. OXYGEN
TEST SITE E

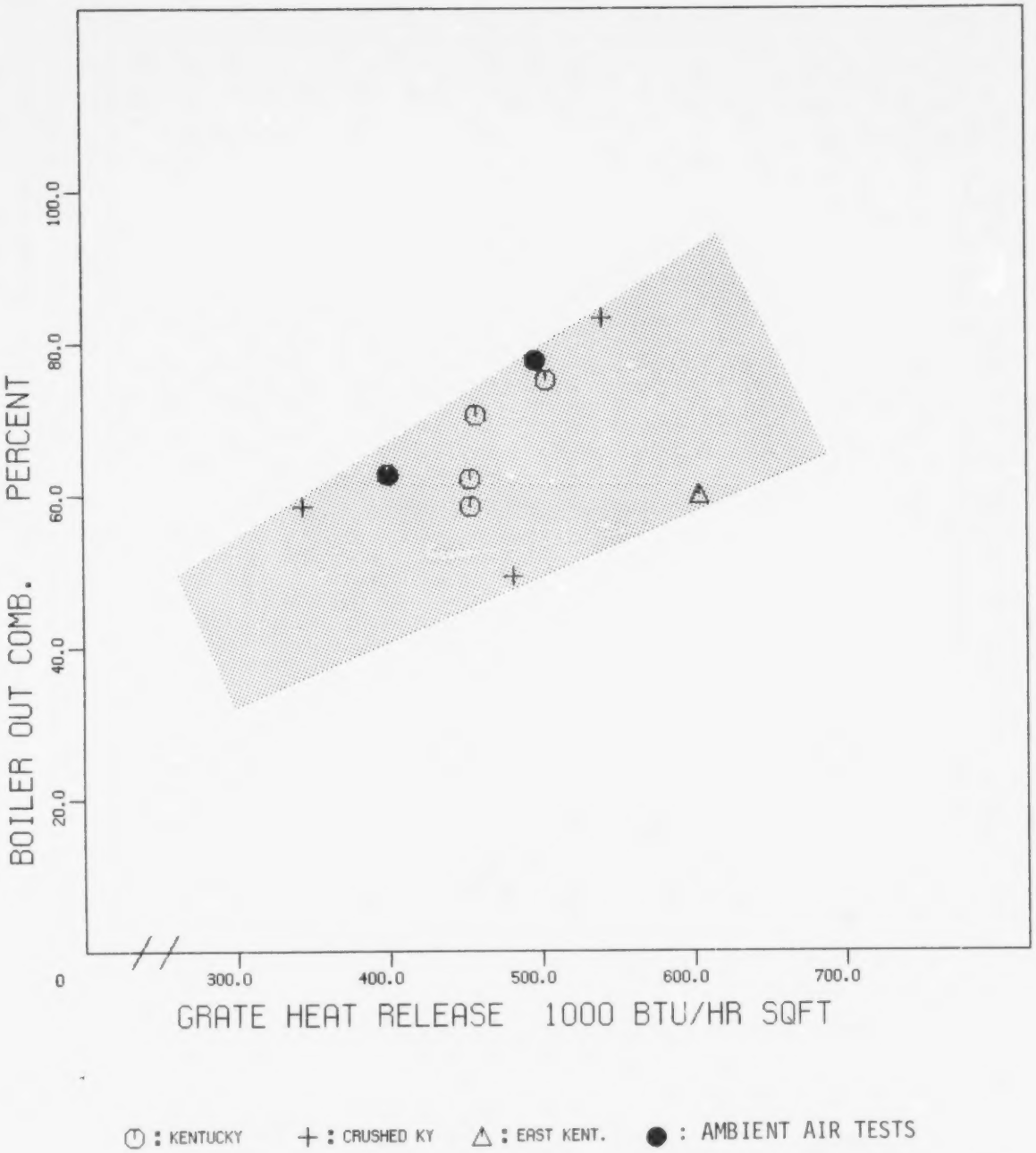


FIG. 5-16
BOILER OUT COMB. VS. GRATE HEAT RELEASE
TEST SITE E

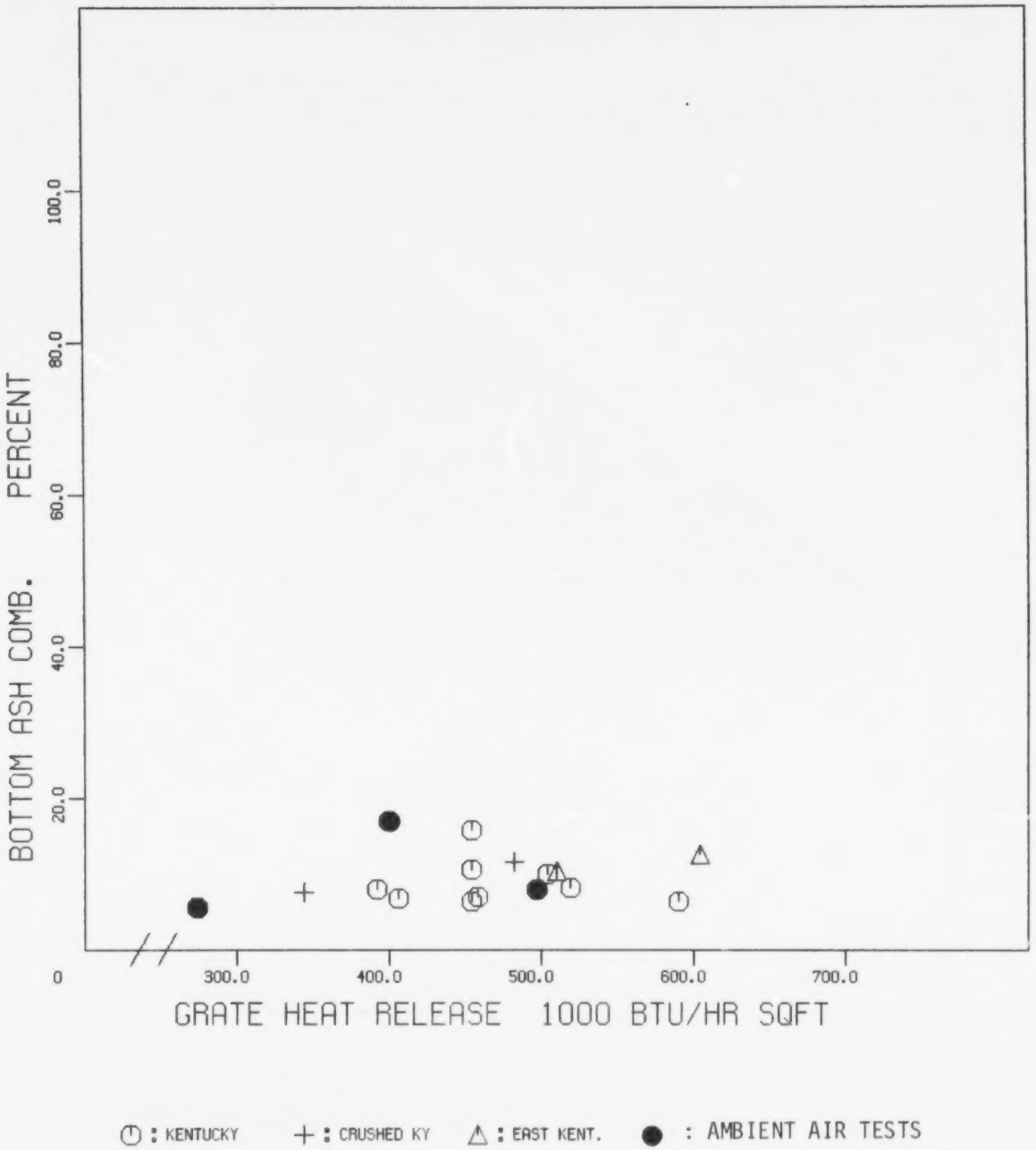


FIG. 5-17
BOTTOM ASH COMB. VS. GRATE HEAT RELEASE
TEST SITE E

Figure 5-18 shows the calculated boiler efficiencies as a function of grate heat release. Data points are keyed to the coal being fired, while the ambient air tests are shown as solid symbols. A general downward trend is seen here with boiler efficiency dropping off as grate heat release increases. At high load -- above 500×10^3 Btu/hr-ft^2 grate area -- the average boiler efficiency was $79.88 \pm 1.48\%$.

Table 5-6 shows the average heat losses for the three coals tested. Kentucky and Crushed Kentucky coals gave almost identical boiler efficiencies. This would be expected because they were from the same mine. East Kentucky coal gave efficiencies which averaged 2.5% lower than the other two coals. The difference appears in two areas, dry gas loss (1.6%) and loss due to combustibles in refuse (0.9%).

TABLE 5-6

AVERAGE HEAT LOSSES BY COAL TYPE

Coal	Dry Gas	Moisture in Fuel	H_2O From H_2 in Fuel	Combustibles in Refuse	Radiation & Unmeasured	Total Losses	Boiler Efficiency, Percent
Kentucky	7.11	0.55	3.85	5.27	2.25	19.03	80.97
Crushed Kentucky	7.20	0.52	3.84	5.23	2.25	19.04	80.96
East Kentucky	8.74	0.59	3.89	6.14	2.17	21.53	78.47

5.3 COAL PROPERTIES

Three coals were tested in this boiler and are described in this section. They are identified here and throughout this report as Kentucky coal, Crushed Kentucky coal and East Kentucky coal.

The Kentucky and East Kentucky coals were from separate mines, while the Crushed Kentucky coal was a specially sized shipment of the Kentucky coal.

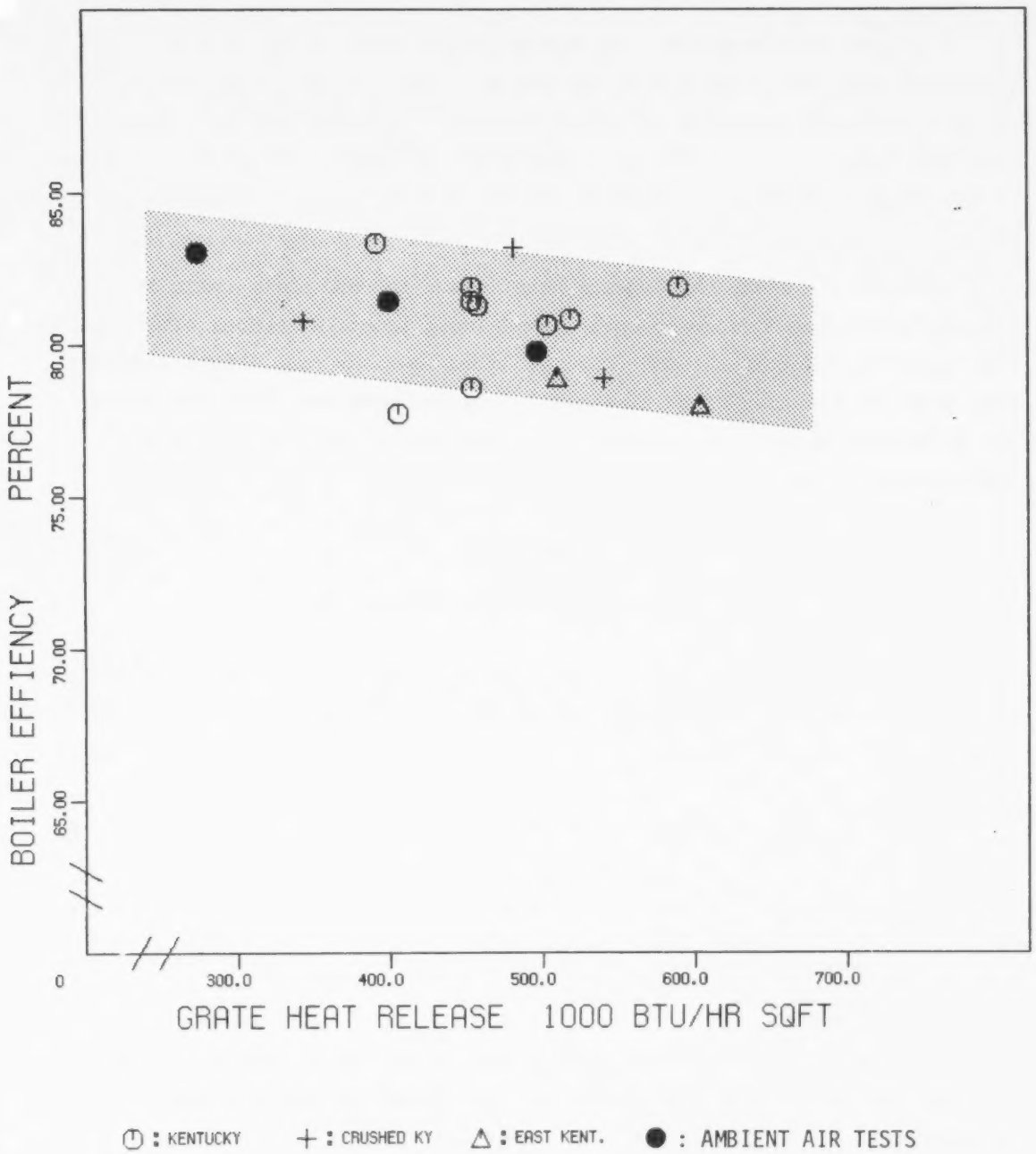


FIG. 5-18
BOILER EFFIENCY VS. GRATE HEAT RELEASE
TEST SITE E

Representative coal samples were taken from the unit's two coal scales during each test that included either a particulate measurement or SASS sample catch. Proximate and ultimate analyses were performed on these samples. A composite sample for each coal was also obtained. The composite sample contained incremental coal samples from each test and was analyzed for ash fusion temperature, Hardgrove grindability index, free swelling index, and minerals in the ash. This section will summarize all test results that appear to be influenced by coal composition and will discuss coal size consistency and sulfur balance data.

5.3.1 Chemical Composition of the Coals

The most significant properties of the coals tested are presented in Table 5-7 on a heating value basis in order to allow for meaningful comparisons between coals.

TABLE 5-7

COAL PROPERTIES CORRECTED TO A CONSTANT 10^6 BTU BASIS

	Kentucky Coal	Crushed Kentucky Coal	East Kentucky Coal
Moisture, lbs/10^6Btu	4.8	4.4	5.0
Ash, lbs/10^6Btu	6.7	7.1	6.5
Sulfur, lbs/10^6Btu	0.67	0.55	0.61

The chemical analyses of each coal sample are grouped by coal and presented in Tables 5-8, 5-9, 5-10, and 5-11. These tables also show the average and standard deviation for each item in the analysis. By comparing these tables, it is evident that all three coals were similar in makeup.

The influence of coal properties on emissions and boiler efficiency is summarized in Table 5-12 with references to the relevant figures. Each of these relationships has been addressed elsewhere in the report but is reviewed here for convenience.

TABLE 5-8

FUEL ANALYSIS - KENTUCKY COAL
TEST SITE E

TEST NO.	2	3	4	5	6	7	8	9	11	17	20	COMP	AVG	STD DEV
PROXIMATE (As Rec'd)														
% Moisture	4.63	6.52	5.77	8.13	6.70	4.81	4.65	5.27	5.23	7.11	8.61	2.03	6.13	1.39
% Ash	5.89	8.68	6.71	10.24	9.71	9.89	5.80	10.25	10.19	8.07	8.33	10.35	8.52	1.73
% Volatile	36.78	34.51	35.44	33.03	32.53	32.97	47.67	32.77	33.73	33.81	32.38	34.12	35.06	4.39
% Fixed Carbon	52.70	50.29	52.08	48.60	51.06	52.33	41.88	51.71	50.85	51.01	50.68	53.50	50.29	3.01
BTU/lb	13651	12546	12942	12021	12417	12957	13519	12666	12790	12530	12460	13193	12773	480
% Sulfur	0.86	0.96	0.74	0.85	0.85	1.01	0.73	0.77	0.89	0.82	0.99	0.95	0.86	0.10
ULTIMATE (As Rec'd)														
% Moisture	4.63	6.52	5.77	8.13	6.70	4.81	4.65	5.27	5.23	7.11	8.61	2.03	6.13	1.39
% Carbon	74.94	70.87	72.97	67.74	70.15	72.43	75.98	71.53	71.43	70.66	69.89	74.33	71.69	2.33
% Hydrogen	4.99	4.75	4.89	4.59	4.60	4.67	5.01	4.58	4.70	4.65	4.58	4.78	4.73	0.16
% Nitrogen	1.51	1.29	1.47	1.31	1.25	0.94	1.20	1.44	1.49	1.19	1.19	0.92	1.30	0.17
% Chlorine	0.20	0.17	0.09	0.14	0.12	0.10	0.15	0.09	0.17	0.08	0.08	0.11	0.13	0.04
% Sulfur	0.86	0.96	0.74	0.85	0.85	1.01	0.73	0.77	0.89	0.82	0.99	0.95	0.86	0.10
% Ash	5.89	8.68	6.71	10.24	9.71	9.89	5.80	10.25	10.19	8.07	8.33	10.35	8.52	1.73
% Oxygen (diff.)	6.98	6.76	7.36	7.00	6.62	6.15	6.48	6.07	5.90	7.42	6.33	6.53	6.67	0.53
ASH FUSION (Reducing)														
Initial Deformation												2700+		
Soft (H=W)												2700+		
Soft (H=½W)												2700+		
Fluid												2700+		
HARDGROVE GRINDABILITY INDEX												47		
FREE SWELLING INDEX												7½		

TABLE 5-9

FUEL ANALYSIS - CRUSHED KENTUCKY COAL
TEST SITE E

TEST NO.	12	13	14	COMP	AVG	STD DEV
PROXIMATE (As Rec'd)						
% Moisture	6.09	5.93	5.04	2.49	5.69	0.57
% Ash	8.76	10.35	8.13	8.10	9.08	1.14
% Volatile	33.00	33.38	34.12	35.05	33.50	0.57
% Fired Carbon	52.15	50.34	52.71	54.36	51.73	1.24
Btu/lb	12793	12565	13135	13508	12831	287
% Sulfur	0.78	0.68	0.67	0.76	0.71	0.06
ULTIMATE (as Rec'd)						
% Moisture	6.09	5.93	5.04	2.49	5.69	0.57
% Carbon	71.65	70.56	73.64	75.79	71.95	1.56
% Hydrogen	4.72	4.61	4.82	5.02	4.72	0.11
% Nitrogen	1.44	1.31	1.32	1.00	1.36	0.07
% Chlorine	0.21	0.14	0.08	0.14	0.14	0.07
% Sulfur	0.78	0.68	0.67	0.76	0.71	0.06
% Ash	8.76	10.35	8.13	8.10	9.08	1.14
% Oxygen (diff)	6.35	6.42	6.30	6.70	6.36	0.06
ASH FUSION (Reducing)						
Initial Deformation				2700+		
Soft (H=W)				2700+		
Soft (H=½W)				2700+		
Fluid				2700+		
HARDGROVE GRINDABILITY INDEX				41		
FREE SWELLING INDEX				6½		

TABLE 5-10

FUEL ANALYSIS - EASTERN KENTUCKY COAL
TEST SITE E

TEST NO.	15	16	COMP	AVG	STD DEV
PROXIMATE (as Rec'd)					
% Moisture	5.04	7.57	2.44	6.31	1.79
% Ash	8.41	8.01	8.26	8.21	0.28
% Volatile	34.92	34.02	36.17	34.47	0.64
% Fixed Carbon	51.63	50.40	53.13	51.02	0.87
Btu/lb	12958	12486	13224	12722	334
% Sulfur	0.81	0.74	0.77	0.78	0.05
ULTIMATE (as Rec'd)					
% Moisture	5.04	7.57	2.44	6.31	1.79
% Carbon	72.59	70.02	74.26	71.31	1.82
% Hydrogen	4.80	4.60	4.90	4.70	0.14
% Nitrogen	1.39	0.86	1.35	1.13	0.37
% Chlorine	0.09	0.07	0.09	0.08	0.01
% Sulfur	0.81	0.74	0.77	0.78	0.05
% Ash	8.41	8.01	8.26	8.21	0.28
% Oxygen (diff.)	6.87	8.13	7.93	7.50	0.89
ASH FUSION (Reducing)					
Initial Deformation			2700+		
Soft (H=W)			2700+		
Soft (H=½W)			2700+		
Fluid			2700+		
HARDGROVE GRINDABILITY INDEX			37		
FREE SWELLING INDEX			4½		

TABLE 5-11

MINERAL ANALYSIS OF COAL ASH
TEST SITE E

Coal	Kentucky	Crushed Kentucky	Eastern Kentucky
Silica, SiO_2	52.67	52.03	49.80
Alumina, Al_2O_3	31.68	33.59	36.27
Titania, TiO_2	3.71	1.66	1.63
Ferric Oxide, Fe_2O_3	6.22	5.34	5.19
Lime, CaO	1.64	1.95	2.07
Magnesia, MgO	0.77	1.08	0.88
Potassium Oxide, K_2O	1.88	2.56	2.07
Sodium Oxide, Na_2O	0.26	0.32	0.25
Sulfur Trioxide, SO_3	0.81	0.76	1.15
Phos. Penoxide, P_2O_5	0.18	0.49	0.43
Undetermined	0.03	0.06	0.06
Silica Value	85.92	86.14	85.95
Base:Acid Ratio	0.12	0.13	0.12
T250 Temperature	2900+°F	2890°F	2900+°F
% Pyritic Sulfur	0.18	0.08	0.15
% Sulfate Sulfur	0.00	0.00	0.01
% Organic Sulfur	0.77	0.68	0.61

TABLE 5-12

RELATIONSHIP BETWEEN COALS FIRED AND EMISSIONS
TEST SITE E

Parameter	Figure No.	Relationship to Coal Type
1. Excess O_2	5-3	East Ky coal fired at highest O_2
2. Particulates (Boiler Outlet)	5-4	None
3. Particulates (Multiclone Outlet)	5-5	Crushed Ky coal highest part.
4. Opacity	5-6	Crushed Ky coal highest opacity
5. Nitric Oxide	5-8	Crushed Ky coal highest NO East Ky coal lowest NO
6. Carbon Monoxide	5-14	Data on Kentucky coal only
7. Combustibles (Boiler Outlet Flyash)	5-16	East Ky coal lowest comb.
8. Combustibles (Bottom Ash)	5-17	None
9. Boiler Efficiency	5-18	None
10. Multiclone Efficiency	5-24	None

5.3.2 Coal Size Consistency

The individual coal samples and the composite coal samples were screened at the site using 1", 1/2", 1/4", #8 and #16 square mesh screens. The results of these screenings are presented in Table 5-13. The average coal size consistency and standard deviation for each of the three coals were determined and are plotted against the ABMA recommended limits for spreader stokers in Figures 5-19, 5-20 and 5-21.

The specially sized Crushed Kentucky coal, which had been ordered for test purposes, turned out to be nearly identical to the Kentucky coal that was not specially sized. This unfortunate occurrence eliminated coal size consistency as one of the variables at this test site.

All three coals fell within the ABMA recommended limits for coal sizing. The Kentucky and Crushed Kentucky coals fall in the center of the ABMA recommended limits while the East Kentucky coal is on the high fines side. Using the generally accepted definition of coal fines -- percent by

TABLE 5-13

AS FIRED COAL SIZE CONSISTENCY
TEST SITE E

	Test No.	PERCENT PASSING STATED SCREEN SIZE 1"	1/2"	1/4"	#8	#16
KENTUCKY COAL	02	93.2	51.9	20.6	8.9	4.8
	03	95.6	66.1	36.9	19.1	11.6
	04	96.8	65.9	29.5	12.7	7.5
	05	95.1	77.0	54.6	31.7	17.2
	06	86.6	56.7	33.8	19.1	12.7
	07	89.5	65.1	33.9	15.3	9.8
	08	87.9	57.0	34.3	18.4	12.2
	09	85.3	62.0	37.4	19.2	12.2
	11	90.4	59.0	31.4	16.0	10.7
	17	93.0	66.1	40.2	20.6	12.4
	20	93.4	73.5	52.0	26.2	9.7
	Composite*	90.6	61.7	35.2	18.5	12.3
	Average	91.5	63.7	36.8	18.8	11.0
CRUSHED KENT COAL	12	97.8	61.4	30.4	13.7	8.5
	13	91.5	54.3	29.0	15.2	10.3
	14	88.5	56.0	32.6	16.2	10.3
	Composite*	95.7	57.1	30.3	14.2	8.5
	Average	92.6	57.2	30.7	15.0	9.7
EASTERN KENT COAL	15	85.7	60.8	40.6	21.7	13.5
	16	89.4	63.9	41.5	22.8	13.5
	Composite*	94.9	73.8	49.5	27.5	16.8
	Average	87.6	62.4	41.1	22.3	13.5

*The composite sample consists of one incremental coal sample from each test on a given coal. It is not included in the average.

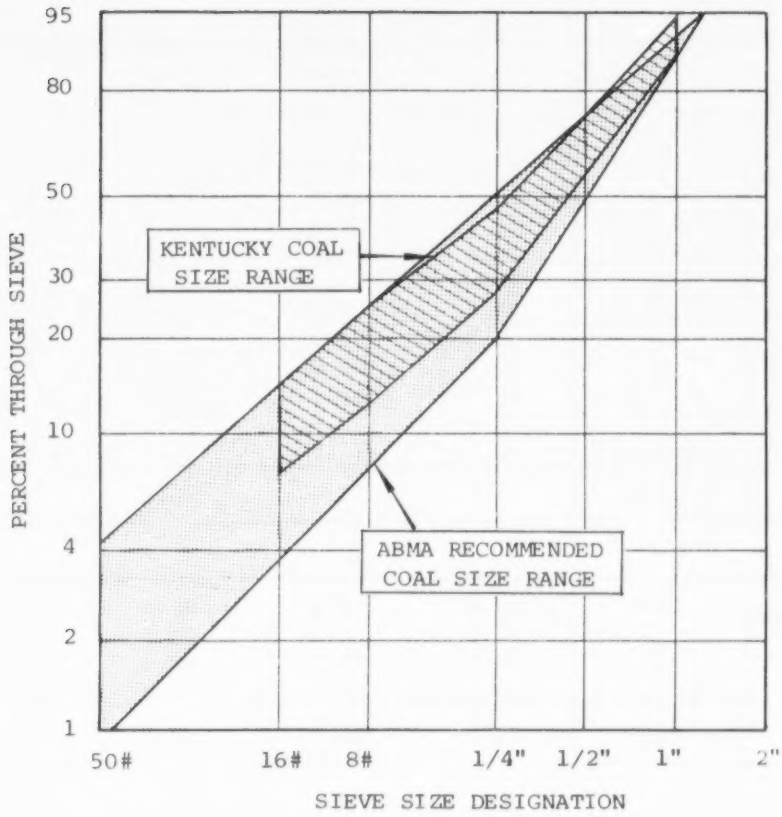


Figure 5-19. Size Consistency of "As Fired" Kentucky Coal vs ABMA Recommended Sizing for Spreader Stokers.

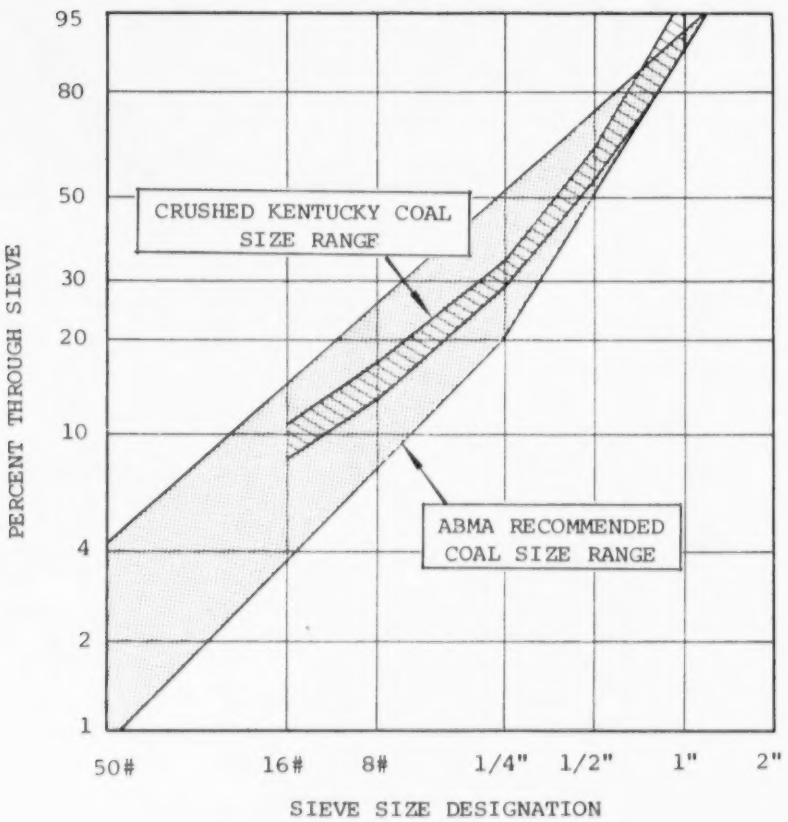


Figure 5-20. Size Consistency of "As Fired" Crushed Kentucky Coal vs ABMA Recommended Sizing for Spreader Stokers.

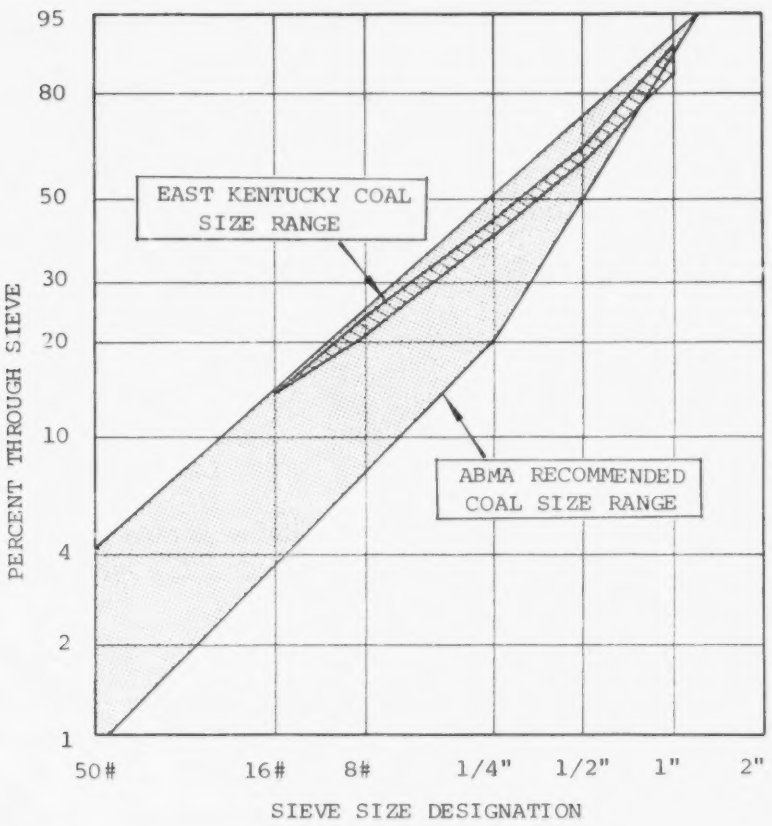


Figure 5-21. Size Consistency of "As Fired" Eastern Kentucky Coal vs ABMA Recommended Sizing for Spreader Stokers.

weight passing a 1/4" square mesh screen -- the percentage of fines in the three coals was: Kentucky coal - 37±10%, Crushed Kentucky coal - 31±2%, East Kentucky Coal - 41±1%.

5.3.3 Sulfur Balance

Sulfur oxides -- SO_2 and SO_3 -- were measured in the flue gas during one test on Kentucky coal and one test on East Kentucky coal. EPA Method 6 and the Shell-Emeryville wet chemical methods were used to make these measurements.

A sulfur balance was calculated for the boiler based on the sulfur content of the fuel and the measured sulfur in the bottom ash, flyash, and flue gas. This sulfur balance is shown in Table 5-14. It shows measurement errors, some serious, resulting in a greater sulfur output than input. The Shell-Emeryville method shows a greater error than EPA method 6. The source of this error has not been determined.

5.4 PARTICLE SIZE DISTRIBUTION OF FLYASH

The purpose of the particle size distribution tests carried out under this program is to accumulate a data bank of particle size distribution data from all types of stoker boilers firing a variety of coals under a variety of firing conditions. This data will be valuable to manufacturers of dust collection equipment and to consulting engineers faced with the task of specifying such equipment.

At test site E, two particle size distribution tests were run at the boiler outlet using SASS cyclones for sizing. Two additional tests were run at the economizer outlet with a Brink cascade impactor. The test conditions for all four particle size distribution tests are given in Table 5-15. Test results are presented in Table 5-16 and Figures 5-22 and 5-23.

In general, the test results show that 10% of the boiler outlet flyash was below three micrometers in diameter, and 25% was below ten micrometers. These results are considered valid for the point sampled, but it should be

TABLE 5-14

SULFUR BALANCE
TEST SITE E

	SULFUR IN FUEL		SULFUR IN BOTTOM ASH			SULFUR IN FLYASH			SULFUR IN FLUE GAS			
Test No.	Fuel Sulfur %	As SO_2 lbs/10^6Btu	Ash Sulfur %	As SO_2 lbs/10^6Btu	Retention %	Ash Sulfur %	As SO_2 lbs/10^6Btu	Retention %	SOx ppm(dry)	As SO_2 lbs/10^6Btu	Fuel Sulfur Emitted* %	Sampling Methodology
16	0.74	1.185	0.08	0.0066	0.6	0.39	0.0351	3.0	780	1.502	127	EPA Method 6
									1273	2.399	202	Shell-Emeryville
17	0.82	1.3 9	0.11	0.0096	0.7	0.25	0.0225	1.7	746	1.411	108	EPA Method 6
									770	1.458	111	Shell-Emeryville

*The imbalance between the sulfur in the fuel and the sulfur emitted can be attributed to measurement error.

TABLE 5-15

DESCRIPTION OF PARTICLE SIZE
DISTRIBUTION TESTS
TEST SITE E

Test No.	Coal	% Design Capacity	O_2 %	OFA*	Particle Size Distribution Methodology Used	Sample Location
11	Kentucky	62	6.5	Low	Brink Impactor	Econ Outlet
14	Crushed Kentucky	69	3.9	High	Brink Impactor	Econ Outlet
16	East Kentucky	62	8.3	High	SASS Cyclones	Boiler Outlet
17	Kentucky	62	6.2	High	SASS Cyclones	Boiler Outlet

*High overfire air (OFA) is the normal mode of operation at this facility

TABLE 5-16

RESULTS OF PARTICLE SIZE DISTRIBUTION TESTS
TEST SITE E

Test Description	Size Distribution % Below 3 µm	Size Distribution % Below 10 µm	Size Concentration lbs/10^6Btu Below 3µm	Size Concentration lbs/10^6Btu Below 10µm
Test 11 Brink Econ Out	11.0	--	0.47	--
Test 14 Brink Econ Out	4.3	--	0.28	--
Test 16 SASS Boiler Out	10.7	26.8	0.48	1.2
Test 17 SASS Boiler Out	9.1	23.3	0.41	1.0

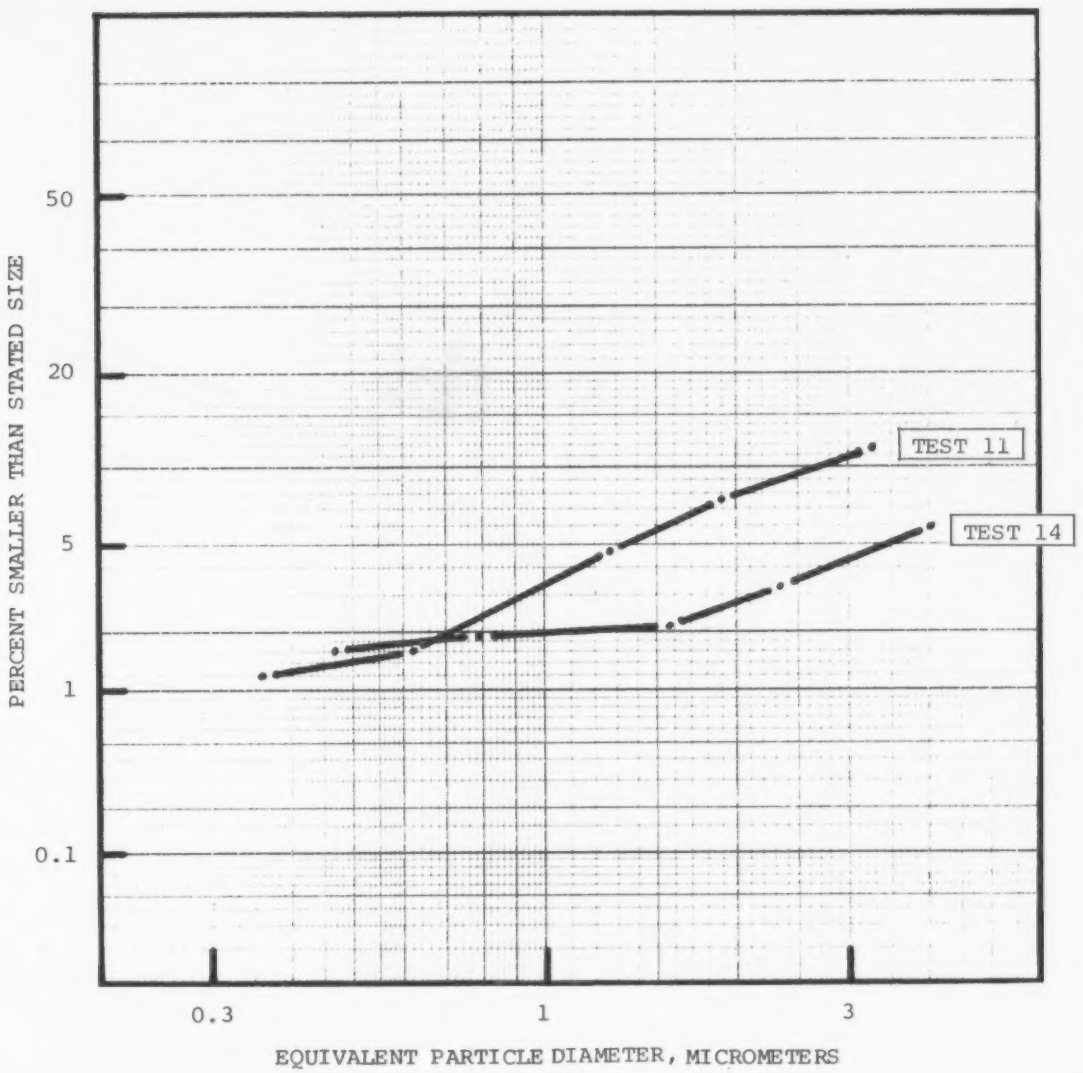


Figure 5-22. Particle Size Distribution at the Economizer Outlet from Brink Cascade Impactor Tests - Test Site E.

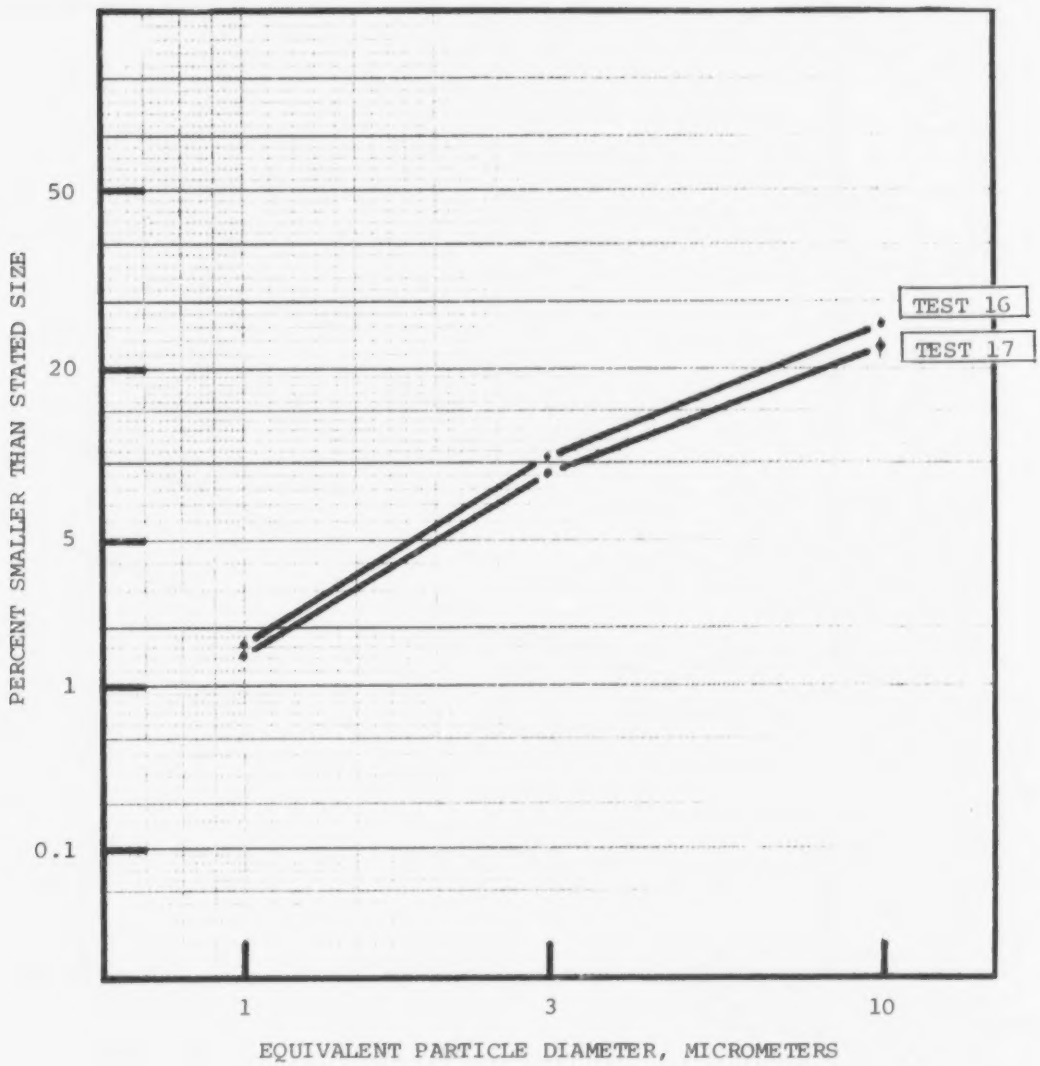


Figure 5-23. Particle Size Distribution at the Boiler Outlet from SASS Cyclone Tests - Test Site E.

noted that both methodologies used, sample from a single point within the duct or breeching. Single point samplers are subject to errors if significant size stratification of the flyash exists within the area being tested.

5.5 EFFICIENCY OF MULTICLONE DUST COLLECTOR

The multiclone dust collector efficiency was determined in thirteen tests under various boiler operating conditions. In each case, collector inlet and outlet dust loadings were measured simultaneously for best accuracy. The results of these tests are shown in Table 5-17 and Figure 5-24.

The efficiency of the multiclone dust collector deteriorated with time during the two months of testing. During the first month of testing the collection efficiency averaged 87% and dipped below 80% only once. During the second month of testing, however, the collection efficiency remained below 70% and averaged 55%. Design efficiency is 96% with 15% of the particles below ten micrometers.

It is theorized that the reduction in collection efficiency resulted from plugging of several cyclone tubes in the collector, perhaps as a result of infrequent cleaning of the multiclone ash hopper.

As a result of this problem, no correlation has been attempted between collection efficiency and other variables such as coal or boiler loading.

5.6 SOURCE ASSESSMENT SAMPLING SYSTEM

Two Source Assessment Sampling System (SASS) tests were run at Test Site E. One test was run on Kentucky coal and one on East Kentucky coal, tests 17 and 16 respectively. The sample catches from these two tests were sent to Battelle Columbus Laboratories where they will be analyzed by combined gas chromatography/mass spectroscopy for total polynuclear content, seven specific polynuclear aromatic hydrocarbons (PAH), and trace elements. The SASS testing is a separately funded segment of this overall test program and all SASS test results will be reported under separate cover at the conclusion of this test program.

TABLE 5-17

EFFICIENCY OF MULTICLONE DUST COLLECTOR
TEST SITE E

Test No.	Coal Type	% Design Capacity	O_2 %	Particulate Loading lb/10^6Btu Collector Inlet	Particulate Loading lb/10^6Btu Collector Outlet	Collector Efficiency, %
02	Kentucky	61	7.6	3.464	--	--
03	Kentucky	46	8.8	2.960	0.313	89.4
04	Kentucky	73	7.2	4.972	0.198	96.0
05	Kentucky	62	9.9	6.188	0.271	95.6
06	Kentucky	65	9.0	2.060	0.335	83.7
07	Kentucky	67	5.2	5.230	1.824	65.1
08	Kentucky	61	6.8	4.493	0.190	95.8
09	Kentucky	57	7.7	3.984	0.641	83.9
11	Kentucky	62	6.5	4.316	1.558	63.9
12	Crushed Kent	65	5.9	3.509	1.852	47.2
13	Crushed Kent	48	9.2	3.631	1.460	59.8
14	Crushed Kent	69	3.9	6.469	3.843	40.6
15	East Kent	70	5.9	5.380	1.746	67.5
20	Kentucky	63	7.0	4.785	2.408	49.7

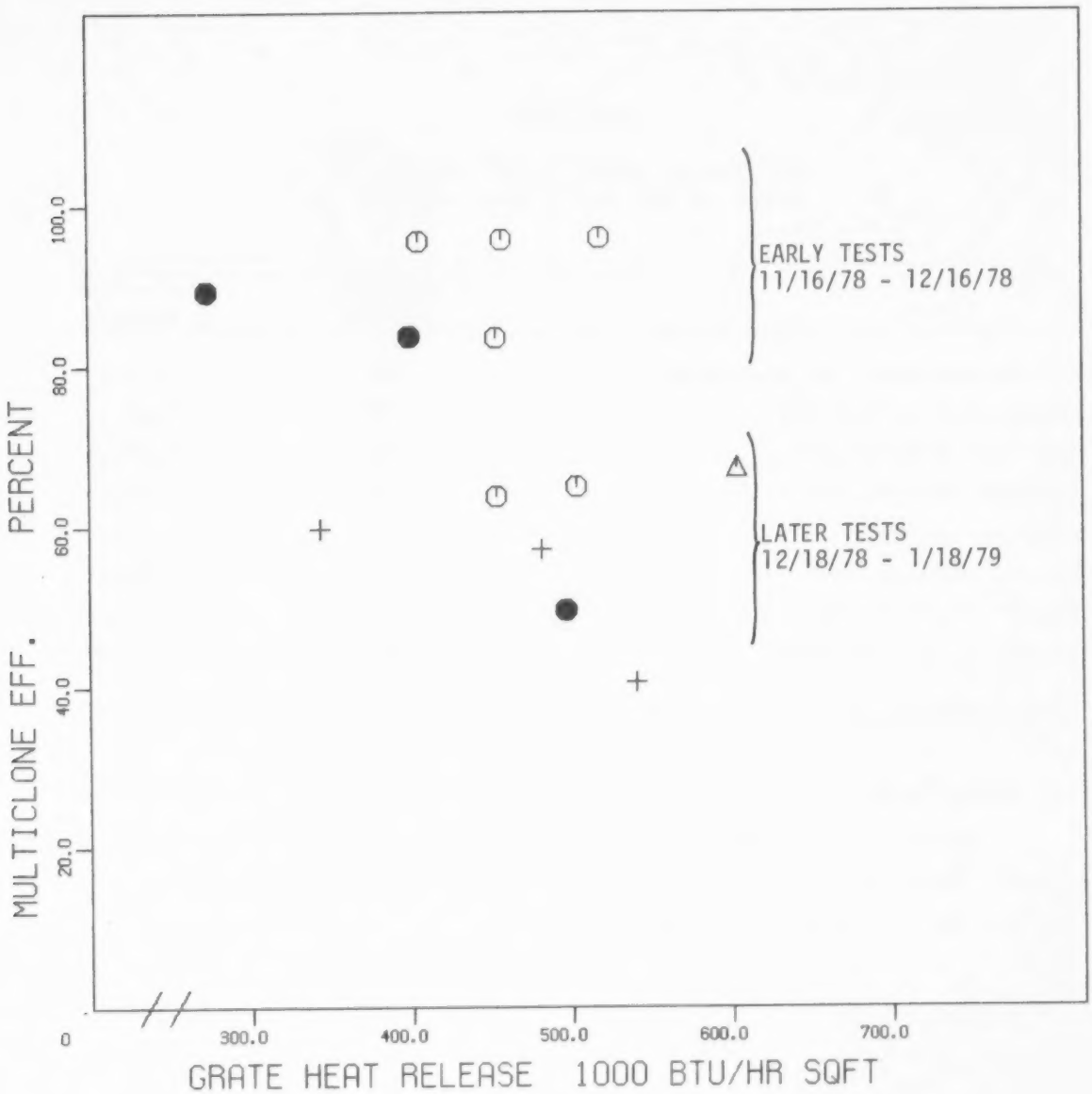


FIG. 5-24
MULTICLONE EFF. VS. GRATE HEAT RELEASE
TEST SITE E

TABLE 5-18

POLYNUCLEAR AROMATIC HYDROCARBONS
SOUGHT IN THE SITE E SASS SAMPLES

Name	Molecular Weight	Molecular Formula
7,12 Dimethylbenz (a) anthracene	256	$C_{20}H_{16}$
Dibenz (a,h) anthracene	278	$C_{22}H_{14}$
Benzo (c) phenanthrene	228	$C_{18}H_{12}$
3-methyl cholanthrene	268	$C_{21}H_{16}$
Benzo (a) pyrene	252	$C_{20}H_{12}$
Dibenzo (a,h) pyrene	302	$C_{24}H_{14}$
Dibenzo (a,i) pyrene	302	$C_{24}H_{14}$
Dibenzo (c,g) carbazole	267	$C_{20}H_{13}N$

5.7 DATA TABLES

Tables 5-19 through 5-22 summarize the test data obtained at Test Site E. These tables, in conjunction with Table 2-1 in the Executive Summary, are included for reference purposes.

TABLE 5-19

PARTICULATE EMISSIONS
TEST SITE E

	Test No.	Coal	Load* %	O_2 %	EMISSIONS lb/10^6Btu	EMISSIONS gr/SCF	EMISSIONS lb/hr	Velocity ft/sec
BOILER OUTLET	02	Kent	61	7.6	3.464	1.601	467	13.99
	03	Kent	46	8.8	2.960	1.245	279	11.98
	04	Kent	73	7.2	4.972	2.366	888	18.97
	05	Kent	62	9.9	6.188	2.367	864	17.53
	06	Kent	65	9.0	2.060	0.961	322	17.65
	07	Kent	67	5.2	5.230	2.848	912	19.92
	08	Kent	61	6.8	4.493	2.203	708	18.49
	09	Kent	57	7.7	3.984	1.824	549	18.47
	11	Kent	62	6.5	4.316	2.160	674	17.94
	12	Crushed	65	5.9	3.509	1.828	582	18.70
	13	Crushed	48	9.2	3.631	1.476	429	18.26
	14	Crushed	69	3.9	6.469	3.824	1204	21.00
	15	E. Kent	70	5.9	5.380	2.801	1118	21.25
	20	Kent	63	7.0	4.785	2.309	818	21.33
ECON OUTLET	02	Kent	61	7.6	2.966	1.319	400	16.58
MECHANICAL COLLECTOR OUTLET	03	Kent	46	8.8	0.313	0.120	29.5	35.69
	04	Kent	73	7.2	0.198	0.092	35.4	58.71
	05	Kent	62	9.9	0.271	0.104	37.8	59.79
	06	Kent	65	9.0	0.335	0.150	52.3	52.42
	07	Kent	67	5.2	1.824	0.880	316	53.19
	08	Kent	61	6.8	0.190	0.089	30.0	50.63
	09	Kent	57	7.7	0.641	0.284	88.3	45.02
	11	Kent	62	6.5	1.558	0.769	243	54.20
	12	Crushed	65	5.9	1.852	0.926	307	53.10
	13	Crushed	48	9.2	1.460	0.578	173	52.06
	14	Crushed	69	3.9	3.843	2.018	715	54.16
	15	E. Kent	70	5.9	1.746	0.909	363	52.99
	20	Kent	63	7.0	2.408	1.162	412	55.50

*Load is expressed as a percent of the boilers design capacity. Maximum obtainable load was 60-70% of design capacity due to a retrofit combustion air system.

TABLE 5-20

HEAT LOSSES AND EFFICIENCIES
TEST SITE E

	TEST NO.	DRY GAS	MOISTURE IN FUEL	H_2O FROM COMBUSTION OF H_2	COMBUSTIBLES IN FLYASH (BLR OUT)	COMBUSTIBLES IN BOTTOM ASH	TOTAL COMBUSTIBLES IN REFUSE	RADIATION FROM BOILER	UNMEASURED	TOTAL LOSSES	EFFICIENCY
KENTUCKY COAL	02	6.54	0.39	3.77	3.25	0.44	3.69	0.75	1.50	16.64	83.36
	03	6.61	0.59	3.89	2.78	0.56	3.34	1.00	1.50	16.93	83.07
	04	7.36	0.52	3.97	4.67	0.52	5.19	0.63	1.50	19.17	80.83
	05	8.82	0.76	3.87	5.81	0.69	6.50	0.79	1.50	22.24	77.76
	06	7.60	0.63	3.88	5.89	1.17	7.06	0.71	1.50	21.38	78.62
	07	6.55	0.43	3.78	5.64	0.76	6.40	0.68	1.50	19.34	80.66
	08	7.32	0.40	3.89	4.52	0.31	4.83	0.75	1.50	18.69	81.31
	09	6.66	0.48	3.74	3.57	1.78	5.35	0.81	1.50	18.54	81.46
	11	6.85	0.48	3.85	3.60	1.55	5.15	0.73	1.50	18.56	81.44
	17	6.81	0.66	3.89	4.00	0.55	4.55	0.68	1.50	18.09	81.91
	20	7.33	0.81	3.85	5.30	0.71	6.01	0.68	1.50	20.18	79.82
	AVG	7.13	0.56	3.85	4.46	0.82	5.28	0.75	1.50	19.07	80.93
CRUSHED KY COAL	12	6.86	0.55	3.86	2.48	0.91	3.39	0.68	1.50	16.84	83.18
	13	8.50	0.55	3.83	3.03	0.82	3.85	0.95	1.50	19.18	80.82
	14	6.25	0.45	3.84	7.70	0.77	8.45	0.63	1.50	21.12	78.88
	AVG	7.20	0.52	3.84	4.40	0.83	5.23	0.75	1.50	19.05	80.96
EAST KY COAL	15	9.97	0.46	3.91	4.62	0.86	5.48	0.65	1.50	21.97	78.03
	16	7.51	0.71	3.87	5.98	0.81	6.79	0.68	1.50	21.06	78.94
	AVG	8.74	0.59	3.89	5.30	0.84	6.14	0.67	1.50	21.52	78.49

TABLE 5-21

SUMMARY OF PERCENT COMBUSTIBLES IN REFUSE
TEST SITE E

	Test No.	Boiler Outlet	Economizer Hopper	Mechanical Collector Hopper	Mechanical Collector Outlet	Bottom Ash
KENTUCKY COAL	02	--	52.71	50.85	--	8.00
	03	--	65.25	55.47	28.8	5.68
	04	--	41.58	42.26	20.0	8.24
	05	--	44.14	38.26	--	6.75
	06	62.3	47.70	57.83	61.2	10.51
	07	75.3	44.34	57.02	67.2	10.10
	08	70.6	47.96	42.70	--	6.97
	09	62.8	30.95	48.59	61.4	16.93
	11	58.6	51.77	34.21	62.0	15.84
	17	--	51.68	33.02	--	6.39
	20	77.8	46.24	48.49	--	8.07
	AVG	67.9	47.67	46.25	50.1	9.41
CRUSHED KENTUCKY COAL	12	49.5	53.98	53.86	56.0	11.53
	13	58.6	53.98	--	56.9	7.70
	14	83.5	53.98	--	--	--
	AVG	63.9	53.98	53.86	56.5	9.60
EAST KENTUCKY COAL	15	60.3	71.20	57.15	--	12.63
	16	--	47.89	56.95	--	10.46
	AVG	60.3	59.55	57.05	--	11.55

TABLE 5-22

STEAM FLOWS AND HEAT RELEASE RATES
TEST SITE E

Test No.	Capacity* %	Steam Flow** 10^3lb/hr	Heat Input*** 10^6Btu/hr	Front Foot Heat Release 10^6Btu/hr-ft	Grate Heat Release 10^3Btu/hr-ft^2	Furnace Heat Release 10^3Btu/hr-ft^3
2	61	109.5	135.0	8.44	392	13.2
3	46	82.9	94.3	5.89	274	9.2
4	73	131.2	178.6	11.16	519	17.4
5	62	110.8	139.6	8.73	406	13.6
6	65	116.9	156.3	9.77	454	15.2
7	67	121.4	173.4	10.84	504	16.9
8	61	109.5	157.7	9.86	458	15.4
9	57	102.0	137.7	8.61	400	13.4
10	61	109.0	156.4	9.78	455	15.3
11	62	112.1	156.2	9.76	454	15.2
12	65	117.6	165.8	10.36	482	16.2
13	48	86.4	118.3	7.39	344	11.5
14	69	124.6	186.1	11.63	541	18.2
15	70	125.8	207.9	12.99	604	20.3
16	62	112.2	175.5	10.97	510	17.1
17	62	111.2	203.1	12.69	590	19.8
18	65	117.9	156.3	9.77	454	15.2
20	63	114.1	171.0	10.69	497	16.7

* The boilers steam loading was restricted to 60-70% of its design capacity because of a retrofit combustion air system. Most of these tests represent the maximum obtainable load on a given day.

** Based on steam flow integrator and corrected upward by a factor of 1.2 to account for a calibration error in the integrator.

*** Based on integrated coal scale counters and higher heating value of coal.

APPENDICES

		Page
APPENDIX A	English and Metric Units to SI Units	92
APPENDIX B	SI Units to English and Metric Units	93
APPENDIX C	SI Prefixes	94
APPENDIX D	Emissions Units Conversion Factors	95

CONVERSION FACTORS

ENGLISH AND METRIC UNITS TO SI UNITS

To Convert From	To	Multiply By
in	cm	2.540
in^2	cm^2	6.452
ft	m	0.3048
ft^2	m^2	0.09290
ft^3	m^3	0.02832
lb	Kg	0.4536
lb/hr	Mg/s	0.1260
$lb/10^6$BTU	ng/J	430
g/Mcal	ng/J	239
BTU	J	1054
BTU/lb	J/kg	2324
BTU/hr	W	0.2929
J/sec	W	1.000
J/hr	W	3600
BTU/ft/hr	W/m	0.9609
BTU/ft/hr	J/hr/m	3459
$BTU/ft^2/hr$	W/m^2	3.152
$BTU/ft^2/hr$	$J/hr/m^2$	11349
$BTU/ft^3/hr$	W/m^3	10.34
$BTU/ft^3/hr$	$J/hr/m^3$	37234
psia	Pa	6895
$"H_2O$	Pa	249.1
Rankine	Celsius	C = 5/9R-273
Fahrenheit	Celsius	C = 5/9(F-32)
Celsius	Kelvin	K = C+273
Rankine	Kelvin	K = 5/9R

FOR TYPICAL COAL FUEL

ppm @ 3% O_2 (SO_2)	ng/J	($lb/10^6$Btu)	0.851 ($1.98x10^{-3}$)
ppm @ 3% O_2 (SO_3)	ng/J	($lb/10^6$Btu)	1.063 ($2.47x10^{-3}$)
ppm @ 3% O_2 (NO)*	ng/J	($lb/10^6$Btu)	0.399 ($9.28x10^{-4}$)
ppm @ 3% O_2 (NO_2)	ng/J	($lb/10^6$Btu)	0.611 ($1.42x10^{-3}$)
ppm @ 3% O_2 (CO)	ng/J	($lb/10^6$Btu)	0.372 ($8.65x10^{-4}$)
ppm @ 3% O_2 (CH_4)	ng/J	($lb/10^6$Btu)	0.213 ($4.95x10^{-4}$)

*Federal environmental regulations express NOx in terms of NO_2; thus NO units should be converted using the NO_2 conversion factor.

CONVERSION FACTORS

SI UNITS TO ENGLISH AND METRIC UNITS

To Convert From	To	Multiply By
cm	in	0.3937
cm^2	in^2	0.1550
m	ft	3.281
m^2	ft^2	10.764
m^3	ft^3	35.315
Kg	lb	2.205
Mg/s	lb/hr	7.937
ng/J	$lb/10^6BTU$	0.00233
ng/J	g/Mcal	0.00418
J	BTU	0.000948
J/kg	BTU/lb	0.000430
J/hr/m	BTU/ft/hr	0.000289
$J/hr/m^2$	$BTU/ft^2/hr$	0.0000881
$J/hr/m^3$	$BTU/ft^3/hr$	0.0000269
W	BTU/hr	3.414
W	J/hr	0.000278
W/m	BTU/ft/hr	1.041
W/m^2	$BTU/ft^2/hr$	0.317
W/m^3	$BTU/ft^3/hr$	0.0967
Pa	psia	0.000145
Pa	$"H_2O$	0.004014
Kelvin	Fahrenheit	F = 1.8K-460
Celsius	Fahrenheit	F = 1.8C+32
Fahrenheit	Rankine	R = F+460
Kelvin	Rankine	R = 1.8K

FOR TYPICAL COAL FUEL

ng/J	ppm @ 3% O_2 (SO_2)	1.18
ng/J	ppm @ 3% O_2 (SO_3)	0.941
ng/J	ppm @ 3% O_2 (NO)	2.51
ng/J	ppm @ 3% O_2 (NO_2)	1.64
ng/J	ppm @ 3% O_2 (CO)	2.69
ng/J	ppm @ 3% O_2 (CH_4)	4.69

SI PREFIXES

Multiplication Factor	Prefix	SI Symbol
10^{18}	exa	E
10^{15}	peta	P
10^{12}	tera	T
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	k
10^{2}	hecto*	h
10^{1}	deka*	da
10^{-1}	deci*	d
10^{-2}	centi*	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p
10^{-15}	femto	f
10^{-18}	atto	a

*Not recommended but occasionally used

EMISSION UNITS CONVERSION FACTORS FOR TYPICAL COAL FUEL (HV = 13,220 BTU/LB)

Reproduced from best available copy.

To Obtain \ Multiply By		% Weight in Fuel S	% Weight in Fuel N	lbs/10^6Btu SO_2	lbs/10^6Btu NO_2	grams/10^6Cal SO_2	grams/10^6Cal NO_2	PPM (Dry @ 3% O_2) SOx	PPM (Dry @ 3% O_2) NOx	Grains/SCF. (Dry @ 12% CO_2) SO_2	Grains/SCF. (Dry @ 12% CO_2) NO_2
% Weight In Fuel	S	1		0.666		0.370		13.2×10^{-4}		1.48	
	N				0.405		0.225		5.76×10^{-4}		.903
lbs/10^6Btu	SO_2	1.50		1		(.556)		19.8×10^{-4}		(2.23)	
	NO_2		2.47				(.556)		14.2×10^{-4}		(2.23)
grams/10^6Cal	SO_2	2.70		(1.8)		1		35.6×10^{-4}		(4.01)	
	NO_2		4.44		(1.8)				25.6×10^{-4}		(4.01)
PPM (Dry @ 3% O_2)	SOx	758		505		281		1		1127	
	NOx		1736		704		391				1566
Grains/SCF (Dry @ 12% CO_2)	SO_2	.676		(.448)		(.249)		8.87×10^{-4}		1	
	NO_2		1.11		(.448)		(.249)		6.39×10^{-4}		

NOTE: 1. Values in parenthesis can be used for all flue gas constituents such as oxides of carbon, oxides of nitrogen, oxides of sulfur, hydrocarbons, particulates, etc.
2. Standard reference temperature of 530°R was used.